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b

EFFECT OF CHEMICAL WETTING
AGENTS ON THE STRENGTH OF
COMPACTED COHESIVE SOILS

A THESIS

Presented to

The Faculty of the Graduate Division

by

Fernando Mejia

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Civil Engineering

Georgia Institute of Technology

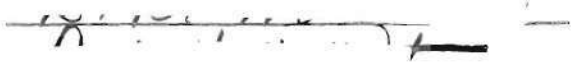
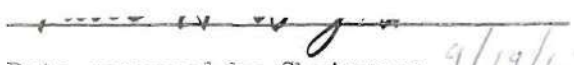
September, 1967

EFFECT OF CHEMICAL WETTING AGENTS
ON THE STRENGTH OF COMPACTED COHESIVE SOILS

Approved:



Chairman



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SUMMARY

In this investigation, a study was made of the effect of chemical wetting agents on the strength of residual soils when compacted at a constant moisture content and compactive effort with different percentages of wetting agents added to the compaction water.

The soil used in this investigation was a reddish brown, well graded micaceous silty sand from the Atlanta area. The soil classification, according to the unified system, is SM.

The chemicals used were all commercially available.

The method of evaluating the chemical effect was to compact the soil with "standard proctor" effort using percentages of surfactant admixture of 0.25, 0.50, 0.75, 1.0, 2.0 and 3.0 percent of total soil moisture. The treated samples were tested in triaxial compression and the strength were compared with those obtained from untreated samples.

Test results for the two categories of admixtures tested (anionic, and nonionic) showed that it is difficult to establish a definite relationship between the strength of the treated soil and the percentages of chemicals used; however, it was observed that increases in percentages of admixture of all surfactants caused an increase in apparent cohesion of the soil. The largest increase in apparent cohesion of the soil occurred at a percentage of admixture of one percent. Increase in percentages of admixture above one percent caused a decrease in apparent cohesion compared to the maximum for all cases.

Increase in percentages of admixture up to 1.5 percent caused a

decrease in the apparent angle of internal friction compared to value obtained for the untreated soil. The largest decrease in the angle of internal friction occurred between 1.0 and 1.5 percent admixture for all cases. Increase in percentages of admixture above 1.5 caused increase in the angle of internal friction for both types of chemical used. For 3.0 percent admixture the angle of internal friction obtained was close to that of the untreated soil for all cases.

Very small changes were observed in the pore water pressure with increases in percent of admixture; but it was observed that the pore water pressure parameter \bar{A}_f decreased for increasing overconsolidation ratio.

CHAPTER I

INTRODUCTION

General

Soil stabilization involves any physical, physico-chemical, and chemical method employed to improve the engineering properties of soils.

Today, soil stabilization has become an important factor in construction in which soils are treated to improve the properties of the foundation material, so that it can carry the applied loads.

Three main factors must be considered in soil stabilization:

(1) Study of the soil properties and required improvement of these properties.

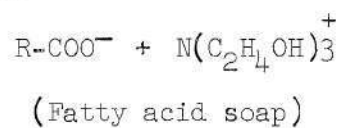
(2) Choice of available materials and methods to improve these properties.

(3) Economic considerations.

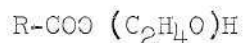
Wetting agents are a group of compounds within the class of "surface active agents". A wetting agent is a material that reduces the surface tension of the water.

Two types of chemicals were used in this research:

(1) Anionic. Those yielding, in solution, surface-active ions bearing a negative charge.



(2) Nonionic. Those which do not ionize in solution.



(Fatty acid polyglycol ester)

Surfactant effectiveness is a function of solubility of the surfactant in the water. Nonionic surfactants show hydrophilic properties through the presence of ether-oxygen type groups that are capable of hydrogen bonding with water. Anionic surfactants are water-soluble because of the innate polar structure of the molecule.

Previous Studies

During the last 15 years the use of chemical products as wetting agents has increased remarkably. These products have been used in textiles, cosmetic industries, and as laundry agents due to their surface tension properties. The use of these surfactant agents has been extended to soil, and so far, the results obtained show good possibilities for stabilizing soils using these products. Although there is a considerable amount of literature concerning chemical stabilization, most of it has been done on unconfined strengths and CBR values. The only tests available showing the effect of chemicals on the effective stress parameters were conducted at the Massachusetts Institute of Technology, (1)* and the results can be summarized as follows:

(1) Massachusetts clayey silt (M-21) treated with 5 percent lime had a higher cohesion intercept \bar{C} . The lime did not have any effect

* Numbers in parentheses refer to numbers in the bibliography.

on the angle of internal friction.

(2) The same soil plus 3 percent cement had a higher friction angle $\bar{\phi}$ as well as cohesion intercept \bar{C} .

Effect of curing time showed the following:

The friction angle $\bar{\phi}$ remains constant with curing time.

Higher envelopes were obtained for prolonged curing times due to an increase in the cohesion intercept.

Research concerning the effect of chemical agents was conducted by J. M. Hoover, D. T. Davidson and J. V. Roegiers at Iowa State University (2). The research consisted of a miniature triaxial shear testing on a quaternary ammonium chloride stabilized loess, which showed that the friction angle tends to decrease with increasing chemical concentration; unfortunately no data was available in the report.

Although most of the research concerning stabilization is not related to the triaxial compression test, it is worthwhile to mention it, because it shows the influence of chemical agents on the other properties of soils.

Research conducted by D. T. Davidson at Iowa State University of Science and Technology (3) to find the effect of six organic cations on plastic limit, liquid limit, shrinkage limit, air dry strength, and rate of slaking of a highly plastic clay resulted in the following:

- (1) Plasticity index was reduced.
- (2) Shrinkage limit was reduced.
- (3) Air dry strength was lowered.
- (4) Surface tension was reduced.
- (5) Swelling was reduced.

(6) Moisture absorption was reduced.

R. C. Mainfort (4) working with sodium silicate found that it is possible to get good bonding of sandy soil using 6 percent or more by weight, but the treatment does not withstand attack by moisture.

T. William Lambe and Alan S. Michaels (5) found that calcium hydroxide used in amounts of 2 percent to 10 percent of the soil weight reduced plasticity and increased strength in granular soils. The same paper mentions that Anilin Furfural has been used to strengthen beach sand and certain types of fine grained soils.

Finally, research conducted by R. L. Nicholls and D. T. Davidson (6) showed that it was possible to cement soil particles with polymers. High polymers increase the air dry strength of soils. They found that bond action apparently depends upon both air water interfaces and the cementing action of the polymer.

The information mentioned above and some more cited in the bibliography constitute most of the literature available related to this subject.

CHAPTER II

MATERIALS AND TEST EQUIPMENT

Soil

The soil used for this study is typical of that encountered in airfield and roadbuilding construction. The soil used was a reddish brown well graded micaceous silty sand from the Atlanta area. A description of the soil is given in Table 1 with the grain size distribution shown in Figure 1. X-ray analysis appears in Figure 2.

Admixtures

The chemicals used are all commercially available. The product name, ionic type, chemical type, manufacturer and data on the chemicals used are shown in Table 2.

The admixtures can be divided into two groups:

- (1) Nonionic
- (2) Anionic

Within the group of nonionic surface active agents, two chemicals were used: Tergitol TP-9, and Polytergent LF-405. Tergitol TP-9 is a nonylphenol chemical type. This chemical has inverse water solubility. It is more soluble in cold water than in hot water. As heat is applied to a clear system, the solution will become cloudy at a certain temperature. This temperature, called "cloud point", is a measure of the solubility characteristic of the surfactant. Maximum efficiency is obtained just below the cloud point.

Table 1. Soil Description

Location: Atlanta Area

Grain Sieve Analysis

	<u>% Finer</u>
Sieve No. 4	100
Sieve No. 10	91
Sieve No. 20	81
Sieve No. 40	68
Sieve No. 80	48
Sieve No. 100	43
Sieve No. 200	24

Hydrometer Analysis

Grain Size

0.07	24
0.04	14
0.02	5

Atterberg Limits 38%

Liquid Limit 30%

Plastic Limit 8%

Specific Gravity 2.68

BPR Classification A-2-4

Unified Soil Classification SM

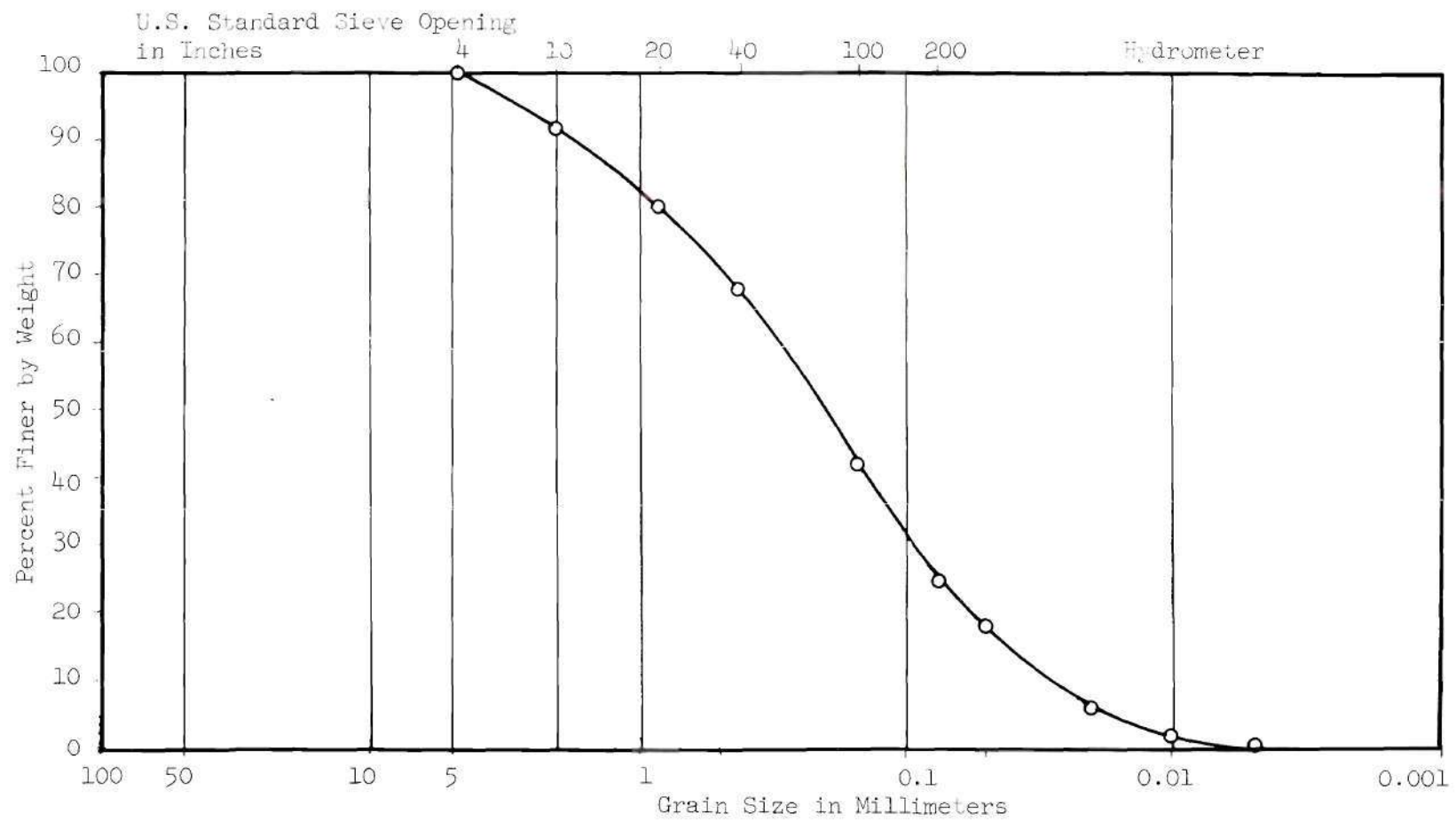


Figure 1. Grain Sieve Analysis

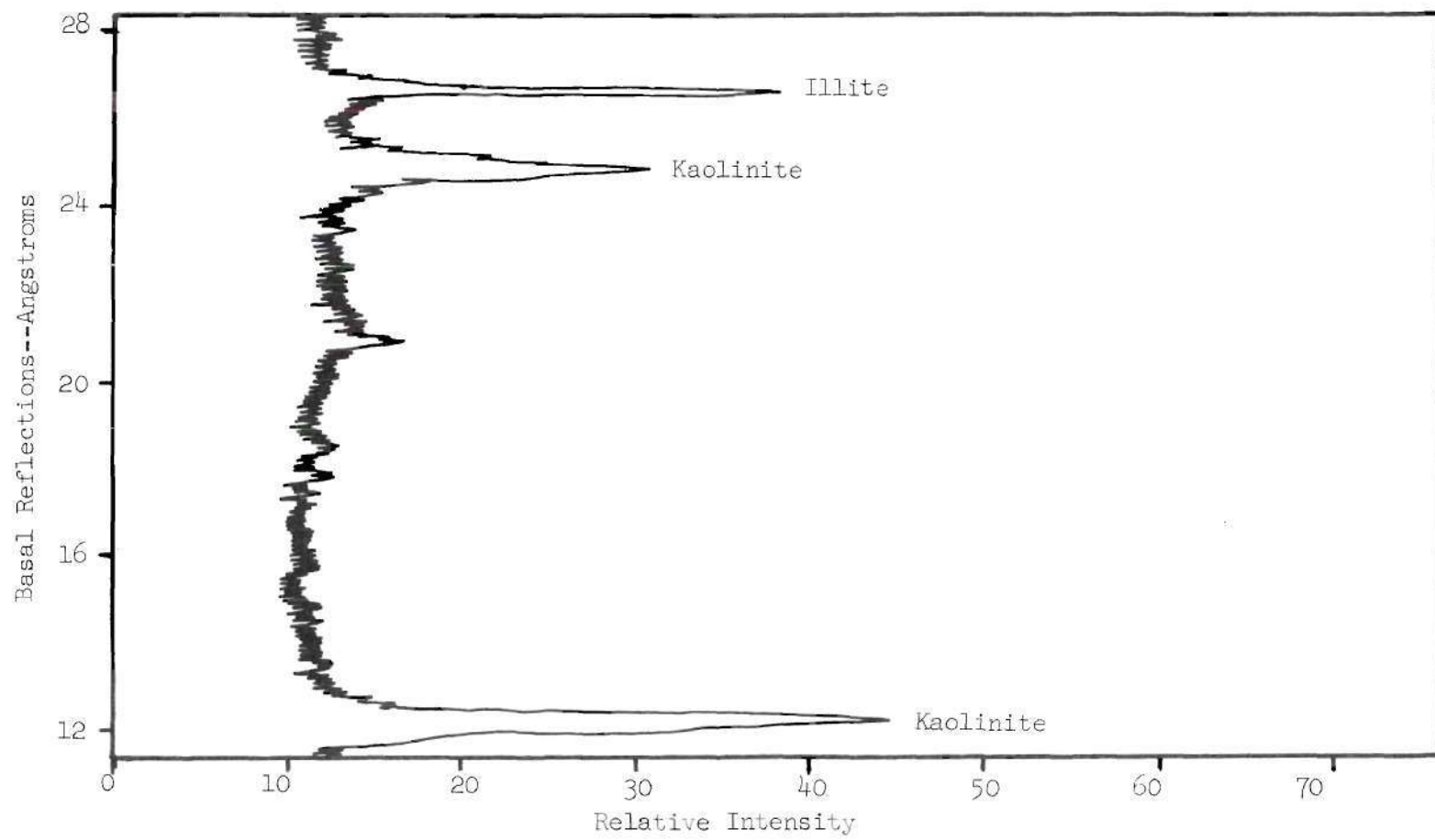


Figure 2. X-Ray Analysis

Table 2. Wetting Agents Data

Product Name	Ionic Type	Chemical Type	Manufacturer	Remarks
Tergitol TP-9	Nonionic	Nonyl Phenyl Polyethylene Glycol Ether	Union Carbide	Slightly Viscous Clear Liquid
Polytergent LF-405	Nonionic	Ethoxylated Nonylphenol	Olin Mathieson	Pale Yellow Slightly Viscous Liquid
Alkanol B	Anionic	Alkyl naphthalene Sodium Sulfonate	DuPont	Light Cream Powder
Nacconol Beads	Anionic	Sodium Alkyl Aryl Sulfonate	National Aniline	Light Bead Dry Strength 40%

Tergitol TP-9 gives rapid wetting and penetration action in electrolytes, but its action may be influenced by the presence of dissolved salts.

Polytergent LF-405 is a linear alcohol alkoxyates designed specifically for low-foaming application, such as mechanical dishwashing, metal cleaning, pulp and paper additives and dairy equipment cleaning. The linear alcohol configuration promotes rapid biodegradation. It is compatible with anionic, cationic, and other nonionic surfactants.

Within the group of anionic surfactants, two chemicals were used: Alkanol B and Nacconol Beads.

Alkanol B is a specialty product for rapid wetting and dispersing where excessive foaming or an electrolyte is undesirable and detergency is unnecessary. It is used in a wide variety of processes involving bleaching and dyeing of textiles, leather and paper. It has good re-wetting properties for paper and paper mill felts, reduces shrinkage in ceramics manufacture, and is an important processing aid in manufacture of dry colors.

Nacconol beads surfactant is an alkyl aryl sulfonate produced from benzene and selected petroleum fractions. It has excellent solubility in water and other neutral solvents, and it is highly efficient and stable even under adverse conditions such as hard water, sea water, hot water, strong alkalis, acids, oxidizing and reducing agents.

Water

The water used in the compaction of the test samples was tap water from the soils laboratory. The impurities present in the water

were assumed to have slight effect on the results. Water analyses are given in Table 3.

Test Equipment

The moisture density test was run using the "Standard Proctor" compaction equipment consisting of a mold $1/30$ cubic foot volume and a 5.5 pound compacting hammer falling 12 inches with the soil compacted in three layers with 25 blows on each layer. From this test, the maximum dry density and the optimum water content were determined. See Figure 3.

The samples to be tested in triaxial compression were prepared using a miniature mold, $1/400$ cubic foot in volume, 30 inches high and 1.5 cm in diameter. The compaction energy was applied using a hydraulic-loading machine previously calibrated to determine the load corresponding to the maximum compactive effort. The calibration curve for the machine is shown in Figure 4.

Pore water pressure was recorded for all tests using a type L Baldwin strain indicator with AC power supply. The pore water cell used was a Dynisco with 100 psi capacity. In Figure 5 is shown the calibration curve for the pore water pressure apparatus.

The load applied on the sample to be tested in triaxial compression was recorded using a 2000 pound capacity, RS-4-type load cell coupled with a load indicator.

Table 3. Mineral Analysis of Tap Water

Constituent	P.P.M.
Silica (SiO_2)	9.5
Chlorine Residual	1.2
Carbon Dioxide (CO_2)	0.00
Dissolved Solids (Conductivity)	30.00
Hardness (CaCO_3)	22.00
Iron (Fe)	0.02
Sulphates (SO_4)	4.00
Alumina (Al)	0.05
Chloride (Cl)	4.00
Calcium (Ca)	7.1
Magnesium (Mg)	1.0
Manganese (Mn)	0.02
Carbonate (CO_3)	3.6
Bicarbonate (HCO_3)	12.2
pH (pH Meter)	7.5

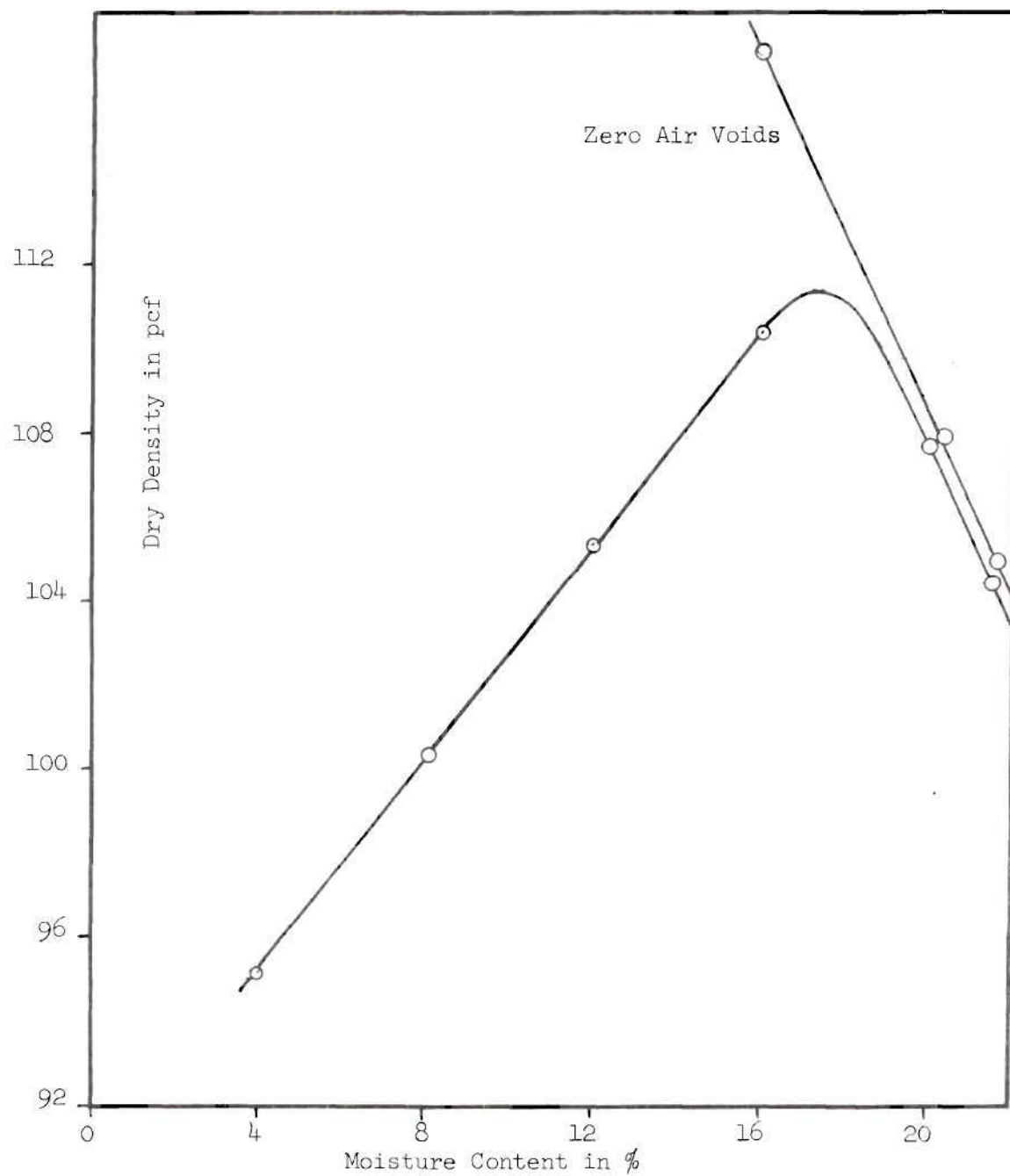


Figure 3. Standard Proctor Moisture-Density Curve
Soil Alone without Admixture

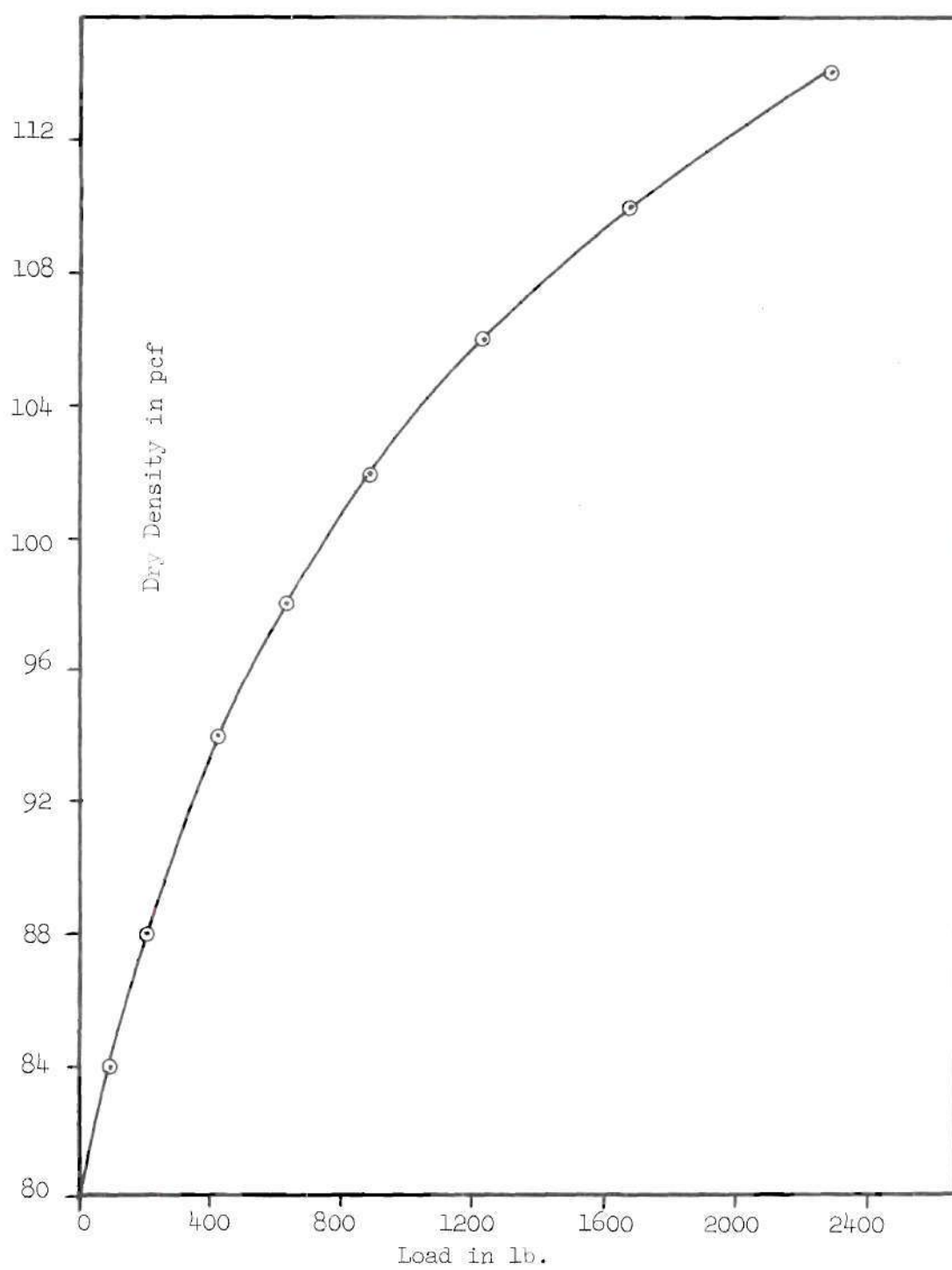


Figure 4. Dry Density vs Load Calibration Curve

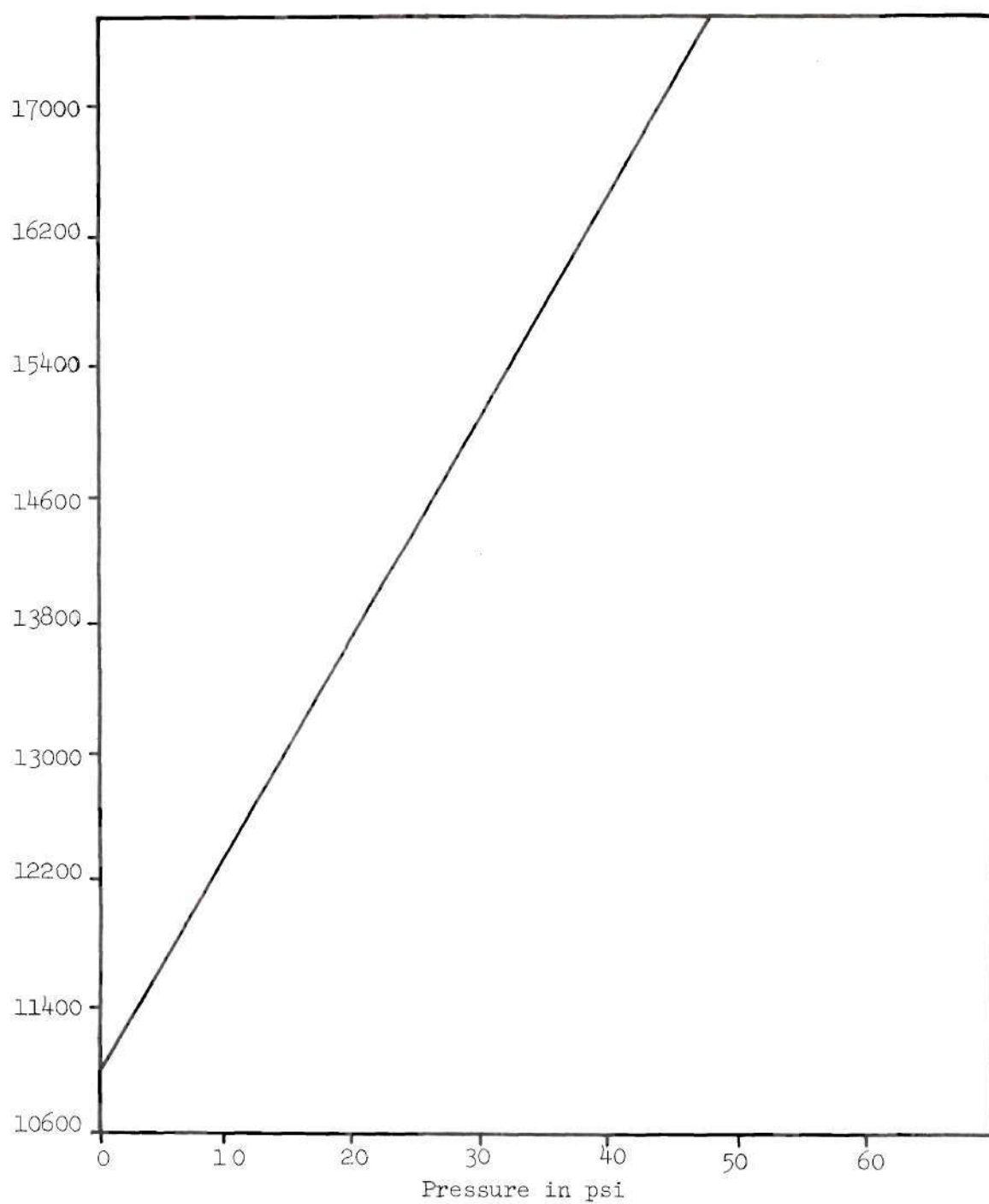


Figure 5. Pore Water Pressure Calibration Curve

CHAPTER III

TESTING PROCEDURE

General

The basic testing program consisted in measuring the change in strength of samples of soil compacted at a specified moisture content and dry density with water treated with the various admixtures. Some of the desirable features in this testing program were:

- (1) A standard size sample and method of compaction.
- (2) A constant density and water content.
- (3) Evaluation by comparing the strength of the treated soil to the strength of the untreated soil.

Three samples of soil, 3 inches high by 1.5 inches in diameter were tested in the triaxial apparatus for every percentage of chemical used. The all around pressures selected were 45, 60 and 75 psi. The rate of strain used was 0.05 inches per minute. The load applied to the soil sample varied from 0 to its maximum value in about 5 minutes.

Recording of pore water pressure was done for all the tests using a strain indicator.

A back pressure of 30 psi was applied to the samples for a period of approximately 3 minutes, and the pore water pressure obtained was recorded as initial reading.

Preparation of Soil and Mixing

The soil was air dried to a uniform moisture content and sieved

through a No. 4 sieve with only the material passing being used in the test. The initial moisture content of the soil was approximately 1.5 percent.

Mixing was done by hand to ensure a uniform moisture content.

Preparation of Soil Samples

The samples were prepared after mixing the soil and the chemical using a miniature mold and applying a static load corresponding to the "Standard Proctor Effort". See Figure 4.

Establishment of a Standard for Comparison

The standard for compaction was defined as the maximum compactive effort obtained from the proctor standard test, (ASTM D-698) and the water content corresponding to that value.

In order to define a standard for comparison, a set of six samples was prepared and then tested in triaxial compression to determine the angle of internal friction, and cohesion intercept for the untreated soil (Figures 6-12).

With these tests, the standard for the testing program was defined, and the values found were:

(1) From the proctor standard test

- A. Maximum dry density - 111 pcf
- B. Optimum moisture - 17.5 %

(2) From the triaxial compression tests

- A. Apparent cohesion intercept in terms of effective stresses. $\bar{C} = 13$ psi
- B. Apparent angle of internal friction in terms of effective stresses. $\phi = 28.5^\circ$

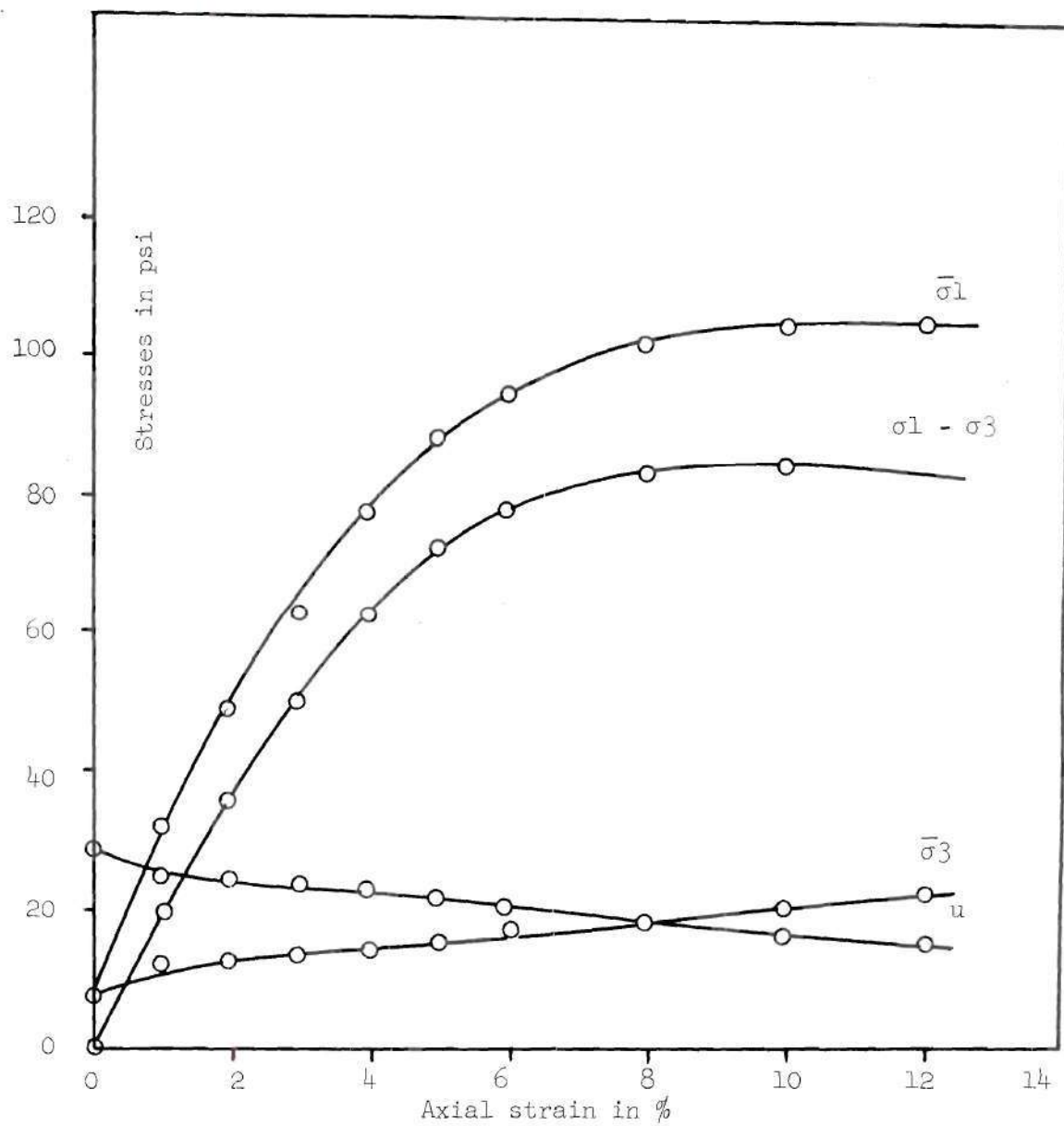


Figure 6. Triaxial Compression Test for Soil without Admixture. All around Pressure: 38 psi

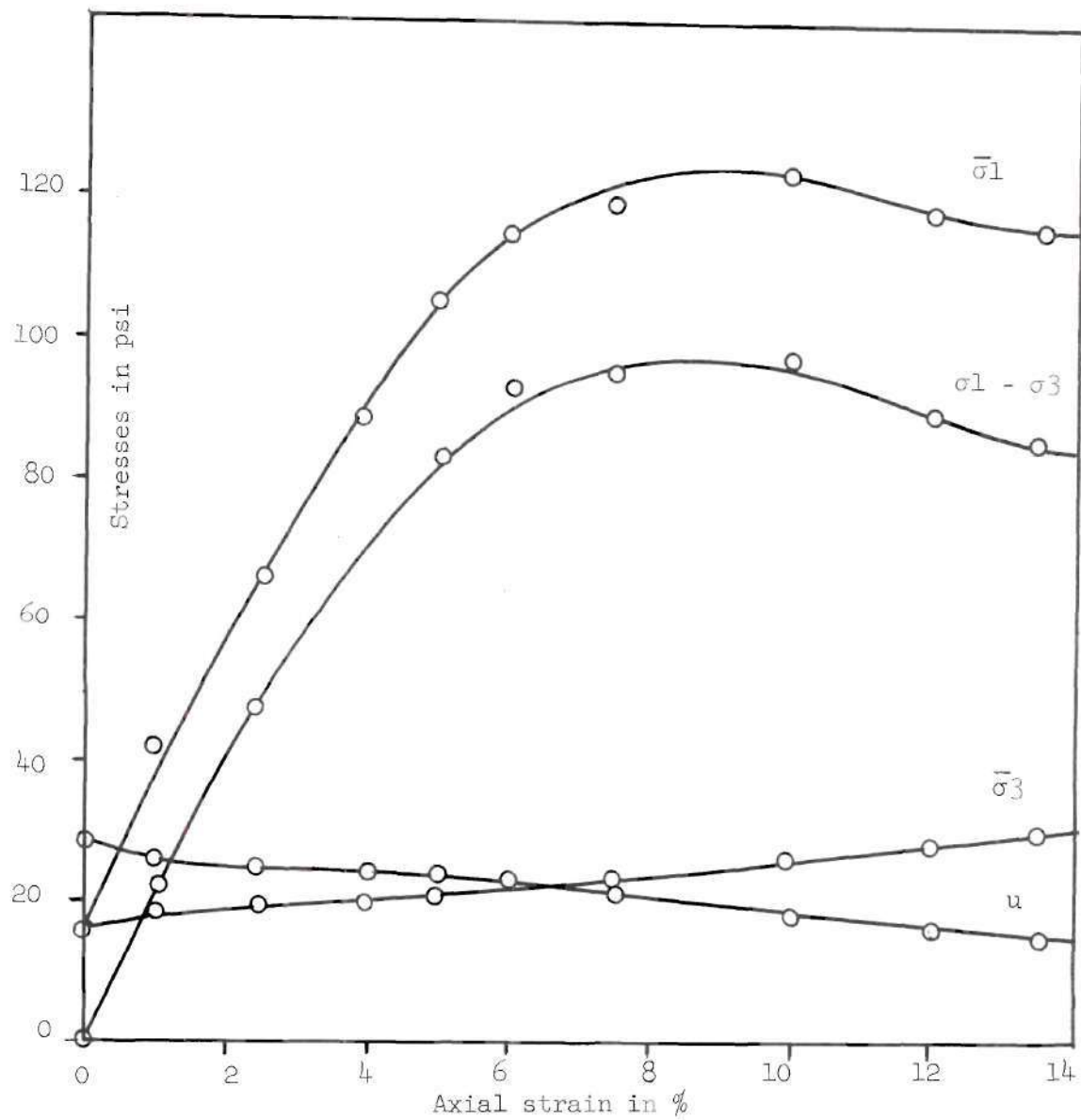


Figure 7. Triaxial Compression Test for Soil without Admixture
All around Pressure: 45 psi

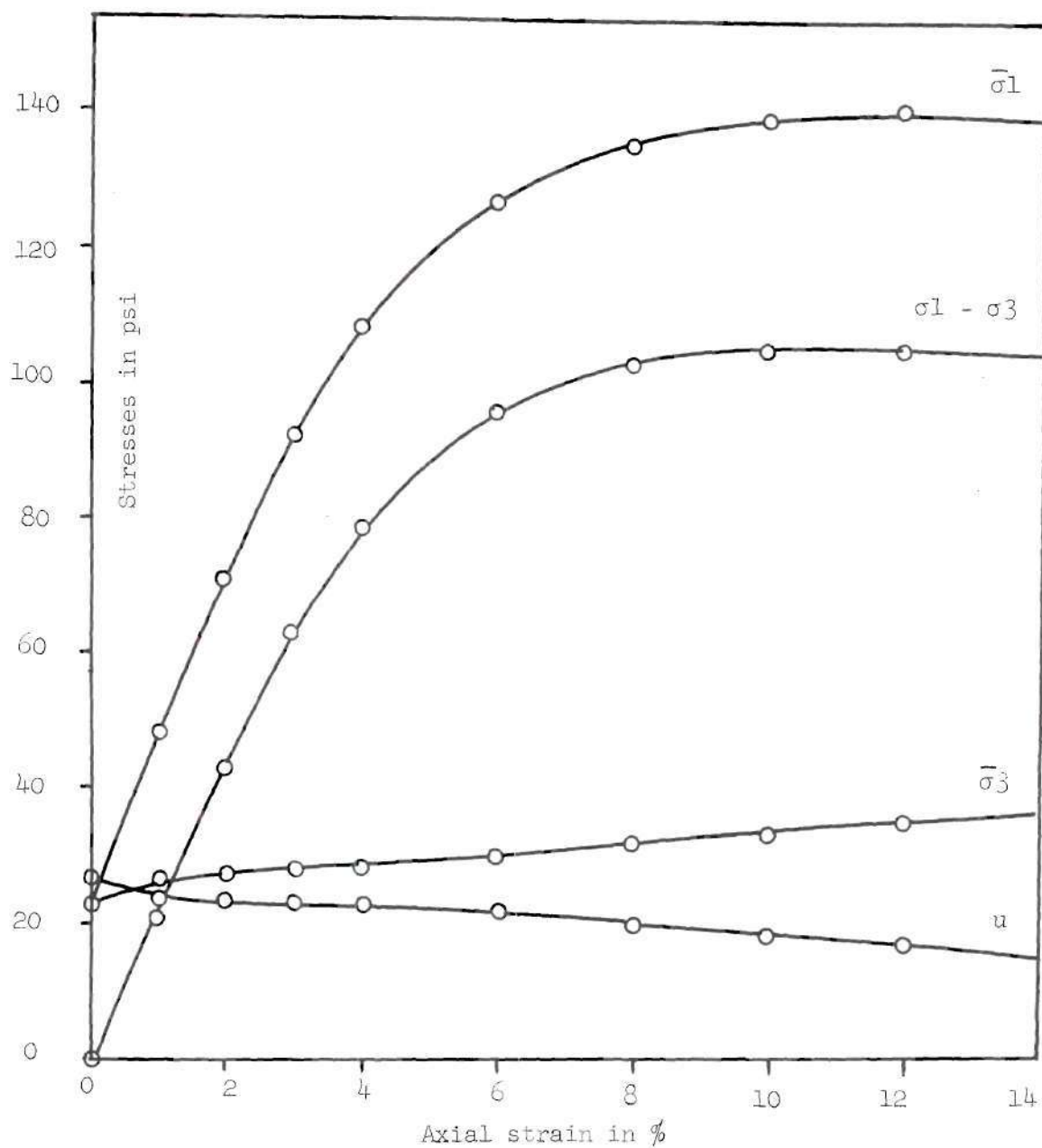


Figure 8. Triaxial Compression Test for Soil without Admixture
All around Pressure: 62 psi

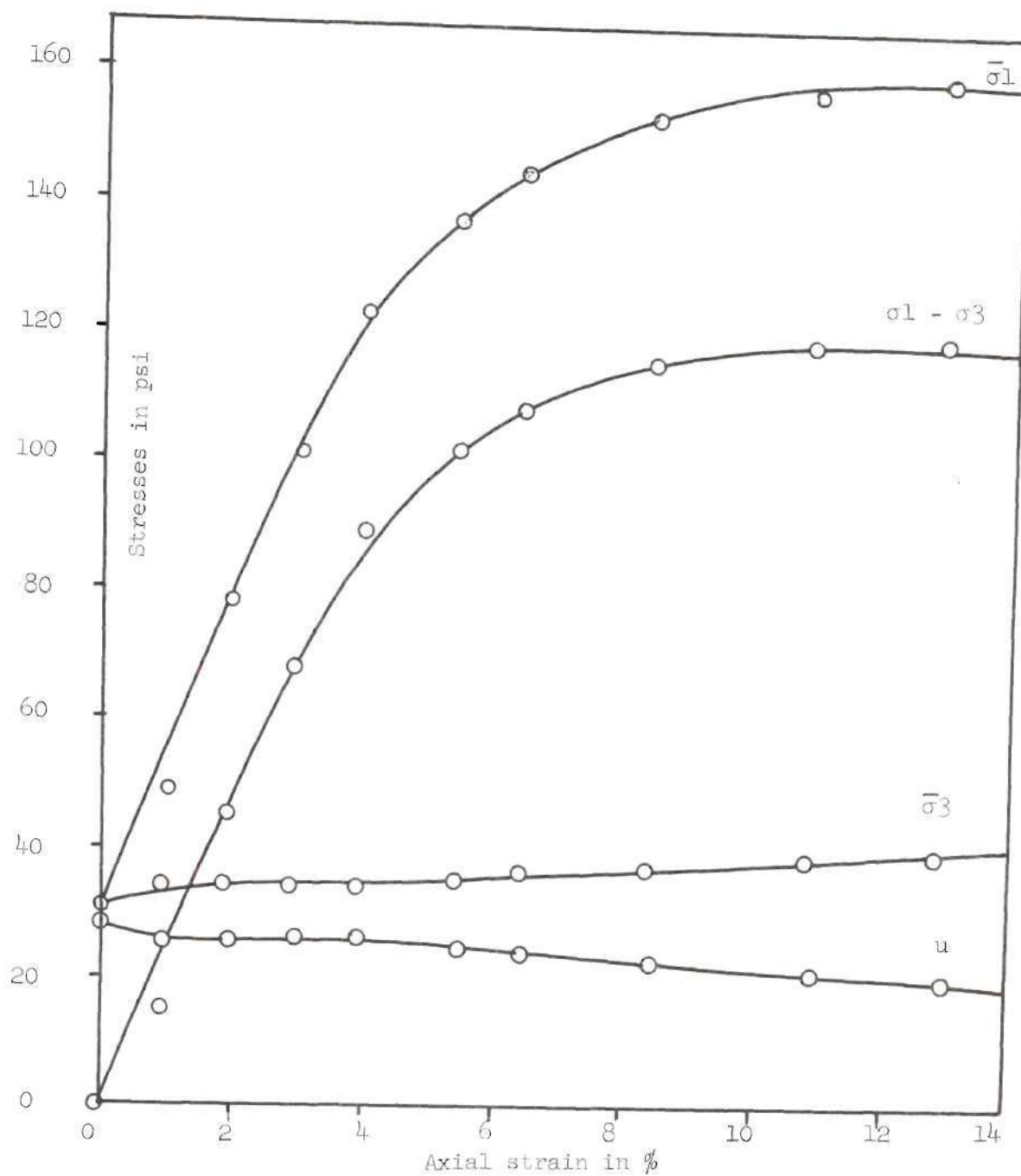


Figure 9. Triaxial Compression Test for Soil without Admixture
All around Pressure 60 psi

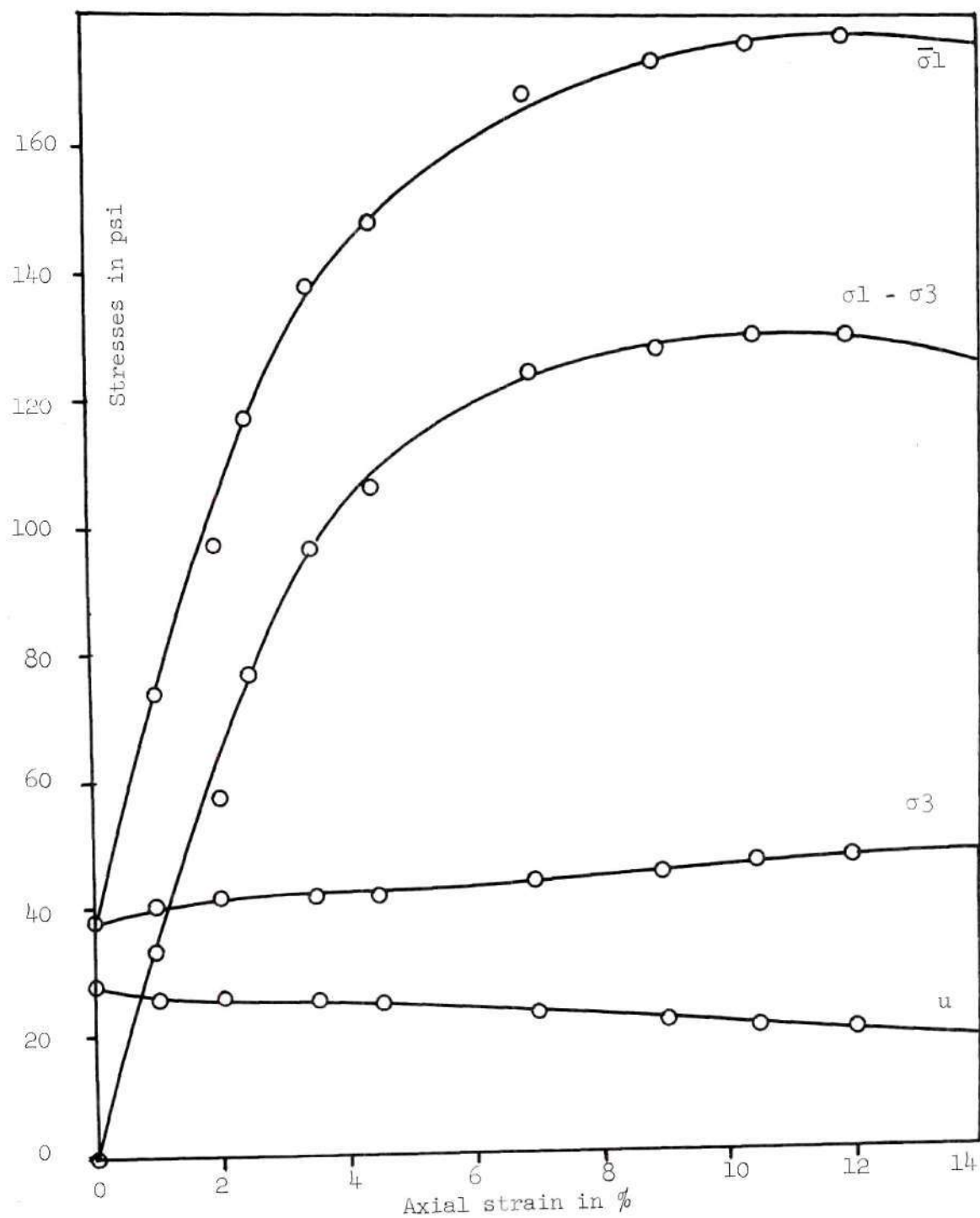


Figure 10. Triaxial Compression Test for Soil without Admixture
All around Pressure: 66 psi

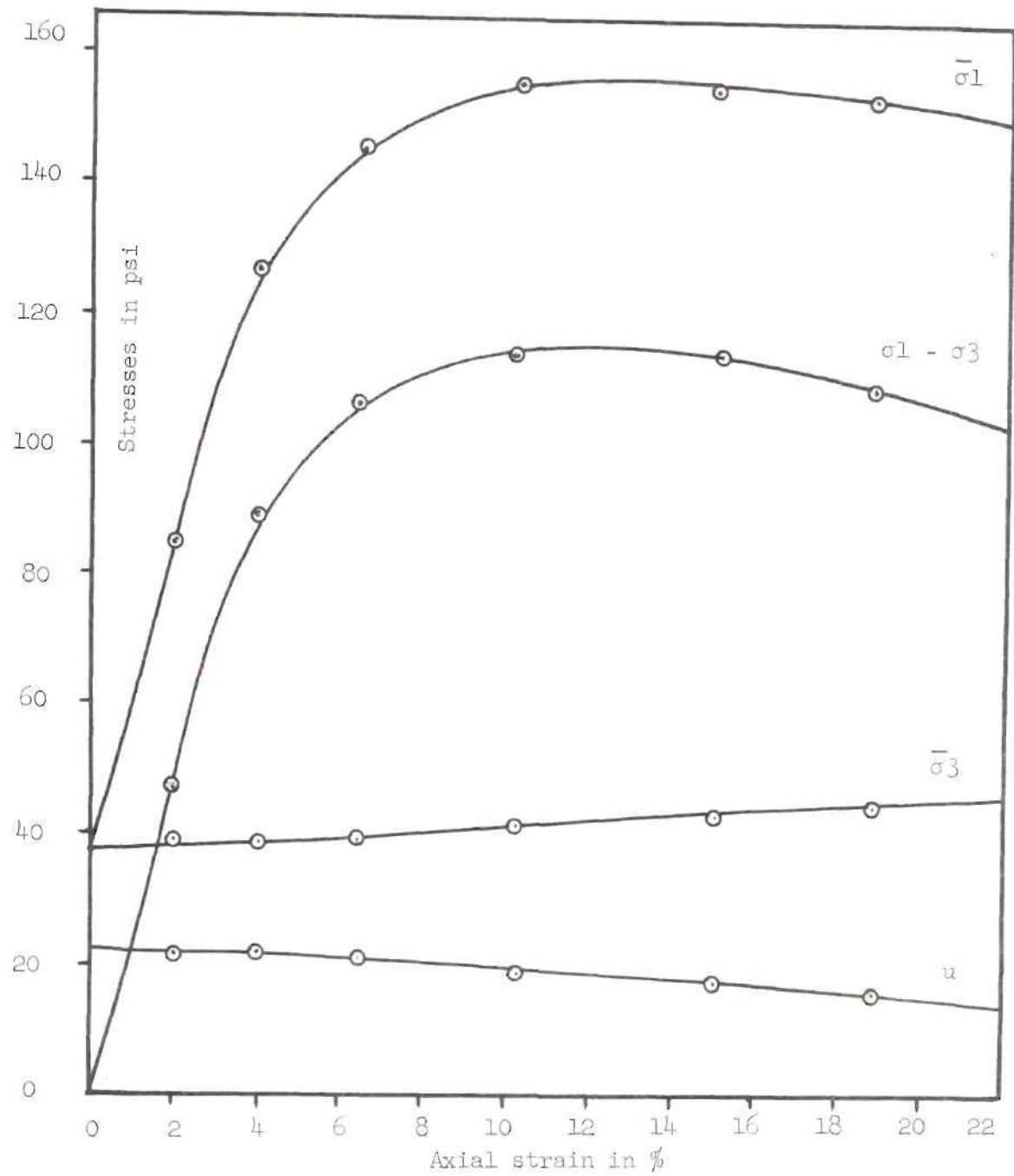


Figure 11. Triaxial Compression Test for Soil without Admixture
All around Pressure: 75 psi

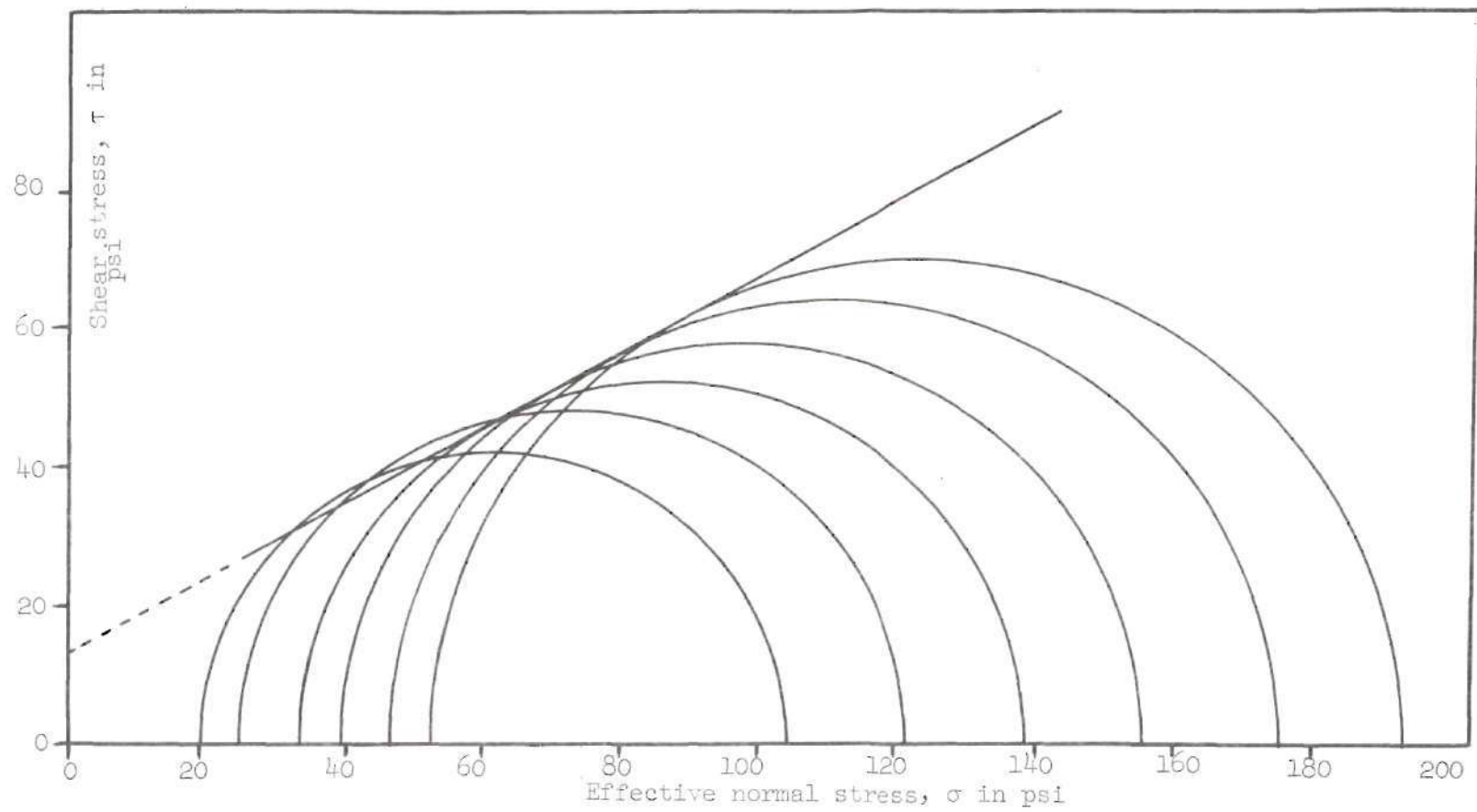


Figure 12. Mohr Circles for Soil without Admixture

Preparation of Chemicals

Special handling and preparation of the chemicals was not required. The chemical required to give the percent solution of moisture was added to the water before mixing the water with the soil. The water and the chemical were mixed for one minute, in a Hamilton Beach Model 33 Mixer, and then added to the soil.

An explanation of why only one minute was used as mixing time is given by the next table.

Table 4. Wetting Time in Distilled Water at 25°C.

<u>Product</u>	<u>Content in %</u>	<u>Wetting Time in Sec.</u>
Poly-	0.05	28.0
Tergent LF 405	0.10	12.5
	0.25	4.0
	0.50	1.8
Nacconol Beads	0.05	58.0
	0.10	26.0
	0.20	12.0
	0.40	5.0
TP-9	No information	
Alkonol B	No information	

Amount of Admixture

The amount of chemical to be added to the soil was based on the total moisture that would be required for the optimum water content obtained for the soil without admixture. For clarity, an example is shown below:

Weight of air-dry soil	-5 lb.
Initial moisture content	-1.5%

105° C. Oven - Dry weight of soil -4.93 lb.

Water required to produce 17.5%
 $M/C = 4.93 \times 0.175 \times 454 \text{ gms/lb} = 391 \text{ gr.}$

Chemical required for 1% solution in soil
 moisture $391 \times 0.01 = 3.91 \text{ gr.}$

Thus, the percentages of chemical used are referred to percentages of the total soil moisture, and not to the soil solids.

Control of Moisture Content

Water content tests were performed for each sample, after testing in triaxial compression. If the actual moisture did not vary more than one percent above or below the standard value, it was considered acceptable.

Water content control was difficult because the samples tested in the triaxial apparatus soaked water when the back pressure was applied.

Selection of Percent Solutions to be Used

Data furnished by the manufacturers did not provide any information concerning concentrations.

H. G. Shirley (7) conducting research at Georgia Tech in 1965, with these chemicals found that percentages above 3 percent produced insignificant changes in the dry density. Therefore the chemicals for this research were used in solutions ranging from 0-3 percent. The test increments were 0.25, 0.50, 0.75, 1.0 and 3.0 percent by weight of water required for the maximum density.

Pore Water Pressure Parameters A and B

- (1) Pore water pressure parameter \bar{A}_p .

The pore water pressure parameter \bar{A}_f was determined for each one of the all around pressures and percentages of admixture. The values are given in Table 5.

(2) Pore water pressure parameter B.

When the samples are 100 percent saturated, the value of the pore water pressure parameter B should be 1. The values obtained are given in Table 6.

To determine the pore water pressure parameter B, two tests were run (Figures 13 and 14) on two samples prepared with the maximum dry density and optimum water content. The first test called Method I was conducted according to the following procedure.

(1) σ_3 and back pressure were increased at the same time to 30 psi. This value was the one taken as reference to measure pore water pressure.

(2) σ_3 was increased to 45 psi. This value corresponded to the lowest chamber pressure used in the testing program.

(3) Consolidation was allowed for 15 minutes. This was roughly the time elapsed before starting the test.

(4) Pore water pressure was noted before and after consolidation.

(5) σ_3 was increased in 5 psi increments up to 80 psi and the corresponding pore water pressure recorded.

The second test, called Method II, was run according to the following procedure:

(1) σ_3 increased from 0 to 45 psi and then the back pressure, to 30 psi.

(2) Consolidation was allowed for 15 minutes.

Table 5. Pore Water Pressure Parameter \bar{A}_F

Product Name	Ionic Type	σ_3	Percent Admixture						
			0.25	0.50	0.75	1.0	1.5	2.0	3.0
			Pore Water Pressure Parameter A_f						
Tergitol TP-9	Nonionic	45	-0.107	-0.07	-0.08	-0.05	-0.13	-0.11	-0.07
		60	-0.07	-0.07	-0.05	-0.06	-0.03	-0.07	-0.03
		75	-0.05	0.02	-0.02	--	-0.01	-0.04	-0.02
Polytergent LF 405	Nonionic	45	-0.13	-0.12		-0.09		-0.09	-0.08
		60	-0.16	-0.06		-0.05		-0.09	-0.06
		75	+0.01	-0.05		-0.03		-0.03	-0.01
Alkanol B	Anionic	45	-0.01	-0.16	-0.07	-0.06		-0.08	-0.16
		60	-0.06	-0.07	-0.02	-0.06		-0.07	-0.04
		75	-0.03	-0.03	-0.06	-0.05		-0.05	-0.03
Nacconol Beads	Anionic	45	-0.11	-0.11	-0.11	-0.11		-0.10	-0.07
		60	-0.07	-0.06	-0.05	-0.05		-0.04	-0.04
		75	-0.03	-0.04	-0.03	-0.01		-0.02	-0.02

Table 6. Pore Water Pressure Parameter B

<u>Method I</u>			<u>Method II</u>		
$\Delta\sigma_3$	Δu	B	$\Delta\sigma_3$	Δu	B
5	2	0.4	5	-2	-0.4
5	3.5	0.7	5	0.5	0.1
5	4.5	0.9	5	1	0.2
5	4	0.8	5	1.5	0.3
5	3	0.6	5	1	0.2
5	3	0.6	5	1.5	0.3
3	2	0.7	7	1.5	0.2
			4	1.5	0.4

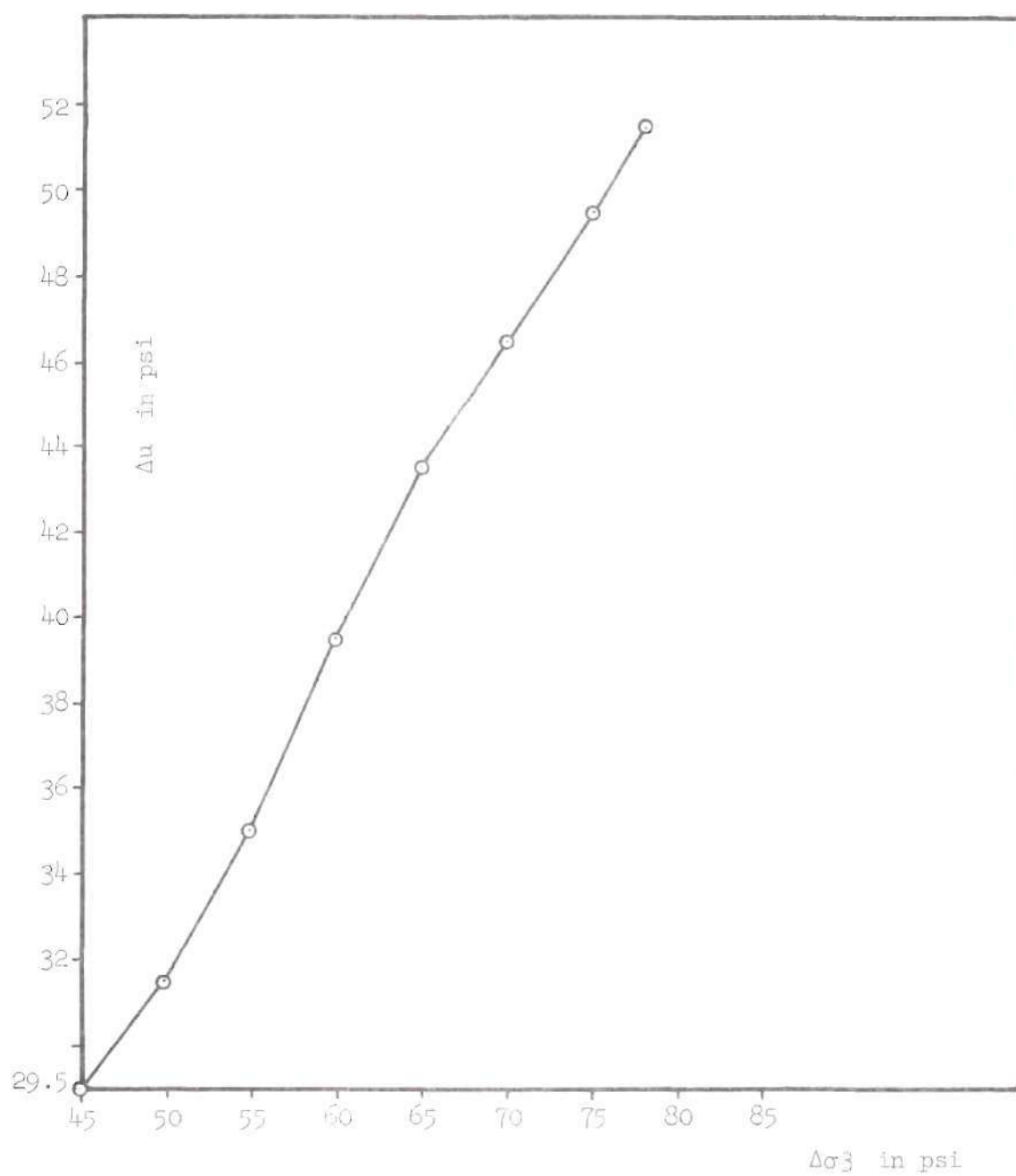


Figure 13. Pore Water Pressure vs $\Delta \sigma_3$, Method I

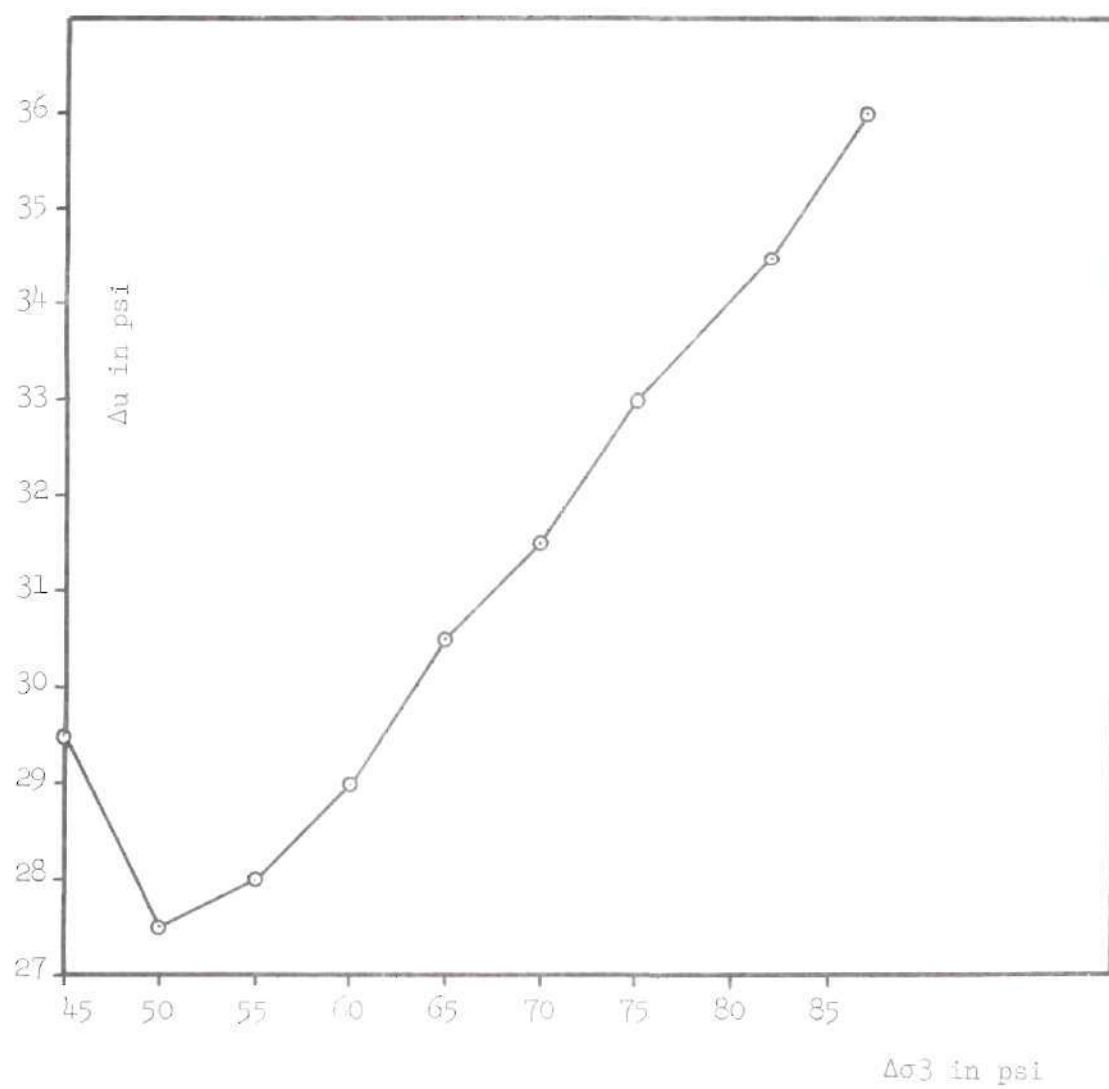


Figure 14. Fore Water Pressure vs $\Delta \sigma_3$, Method II

(3) Pore water pressure was recorded.

(4) σ_3 was increased in 5 psi up to 85 psi and the pore water pressure recorded.

CHAPTER IV

REPRESENTATION AND EVALUATION OF TEST RESULTS

General

For many years, the effective stress in soil has been defined by the equation:

$$\bar{\sigma} = \sigma - u \quad (1)$$

where $\bar{\sigma}$ effective stress

σ total stress

u pore water pressure

For saturated clays, it has been shown that shear strength and consolidation characteristics depend on the effective stress determined in this way. In partially saturated soils, however, different pressures will exist in the pore air and pore water phases. Consideration of this fact led Bishop (8) to propose another equation to compute the effective stresses in partially saturated soils. This equation is:

$$\bar{\sigma} = \sigma - U_a + X (u_w - u_a)$$

where U_a pore air pressure

u_w pore water pressure

X empirical constant which will vary with degree of saturation

However, for the purpose of this research, the evaluation of test results will be done assuming that the effective stress is given by Equation 1.

Graphical Representation of Results

A strain vs. $\overline{\sigma_1}$, $\overline{\sigma_3}$, $(\sigma_1 - \sigma_3)$ and u curves were plotted for each all around pressure, and then the Mohr stress circles were drawn to determine the apparent cohesion and angle of internal friction.

Admixture - Apparent Cohesion

An admixture - apparent cohesion curve was plotted for the soil with the test increments of admixture used in the testing program.

Admixture - Apparent Angle of Internal Friction

An admixture - apparent angle of internal friction curve was plotted for the soil to study the effect of different percentages of admixture on the angle of internal friction.

Admixture - Strength

To determine the effect of admixture on the strength, $\frac{(\sigma_1 - \sigma_3)_f}{(\overline{\sigma_3})_f}$ was plotted versus percent admixture for every chamber pressure. This relation was chosen because soils appear to conform to a Mohr-Coulomb failure criterion.

Test Results

In figures 15, 16, 17 and 18 are shown the results representing the strength of the soil versus percent admixture. All test results show same changes of $\frac{(\sigma_1 - \sigma_3)_f}{(\overline{\sigma_3})_f}$ with increasing percentages of admixture. These changes vary with the all around pressure, σ_3 .

The effect of the chemical on the soil seems to be very small assuming that these agents do not change optimum moisture and maximum density. If any changes occur, then the test results changes reflect

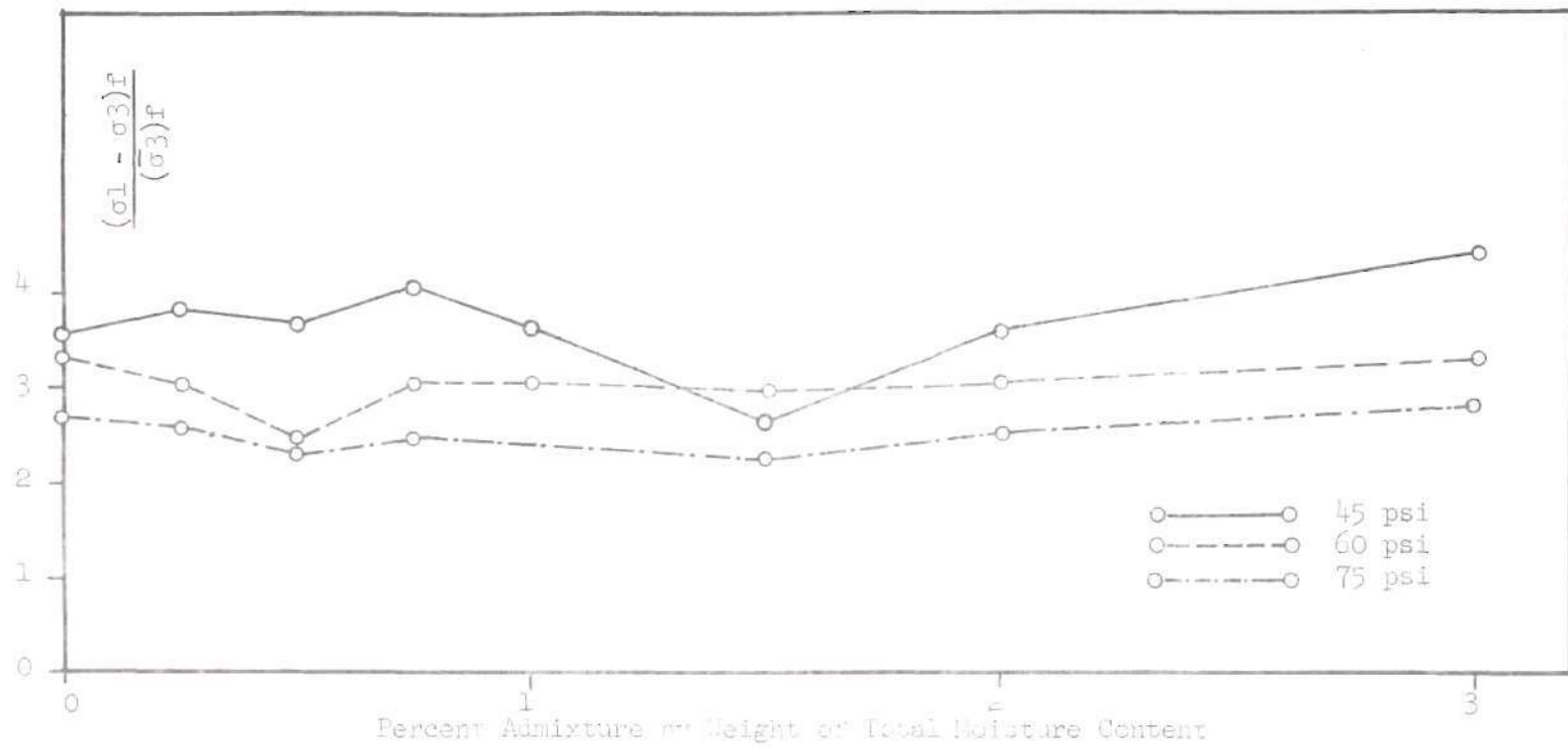


Figure 15. Relationship of $\frac{(\sigma_1 - \sigma_3)f}{(\sigma_3)f}$ and Admixture Tergitol TP-9

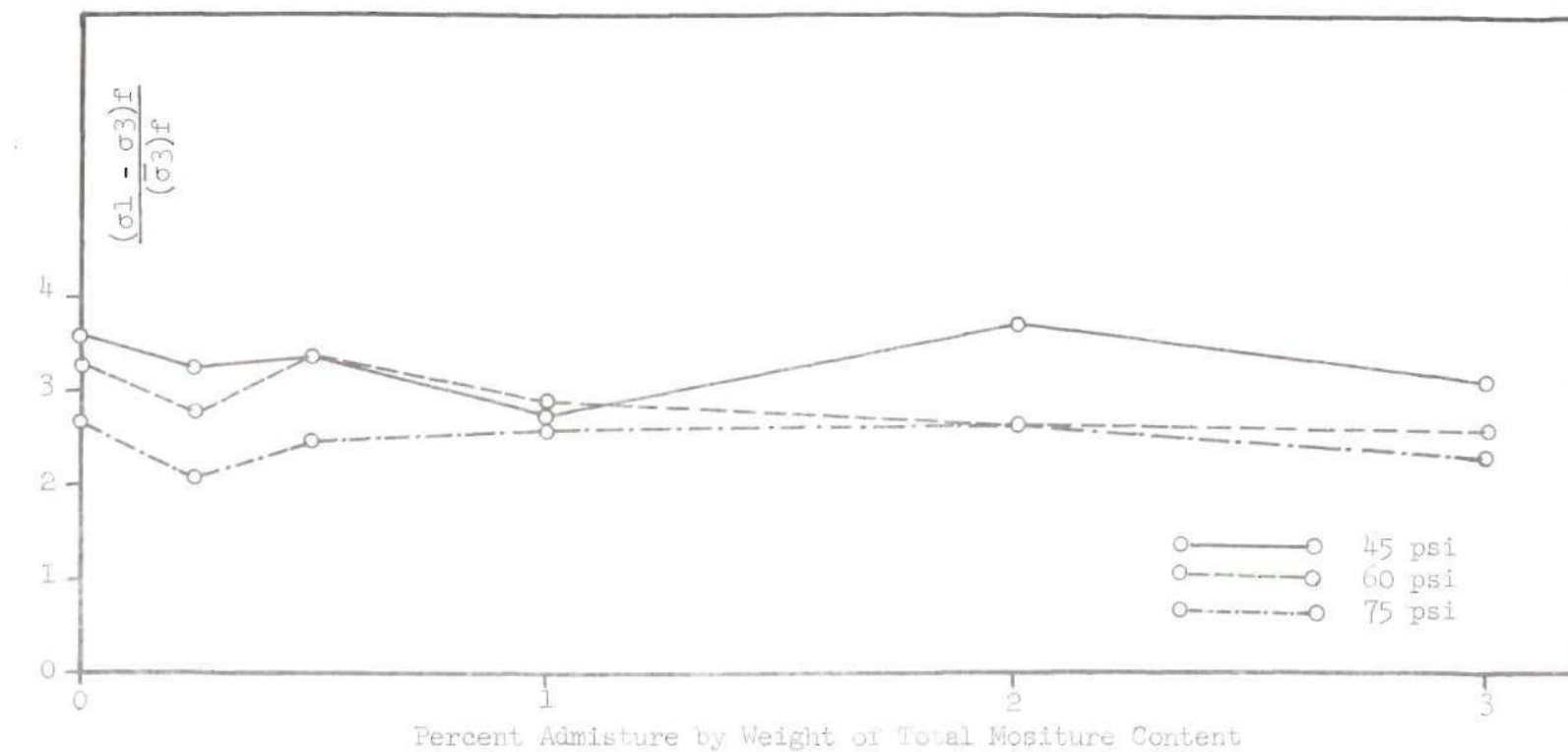


Figure 16. Relationship of $\frac{(\sigma_1 - \sigma_3)f}{(\sigma_3)f}$ and Admixture Polytergent LF-405

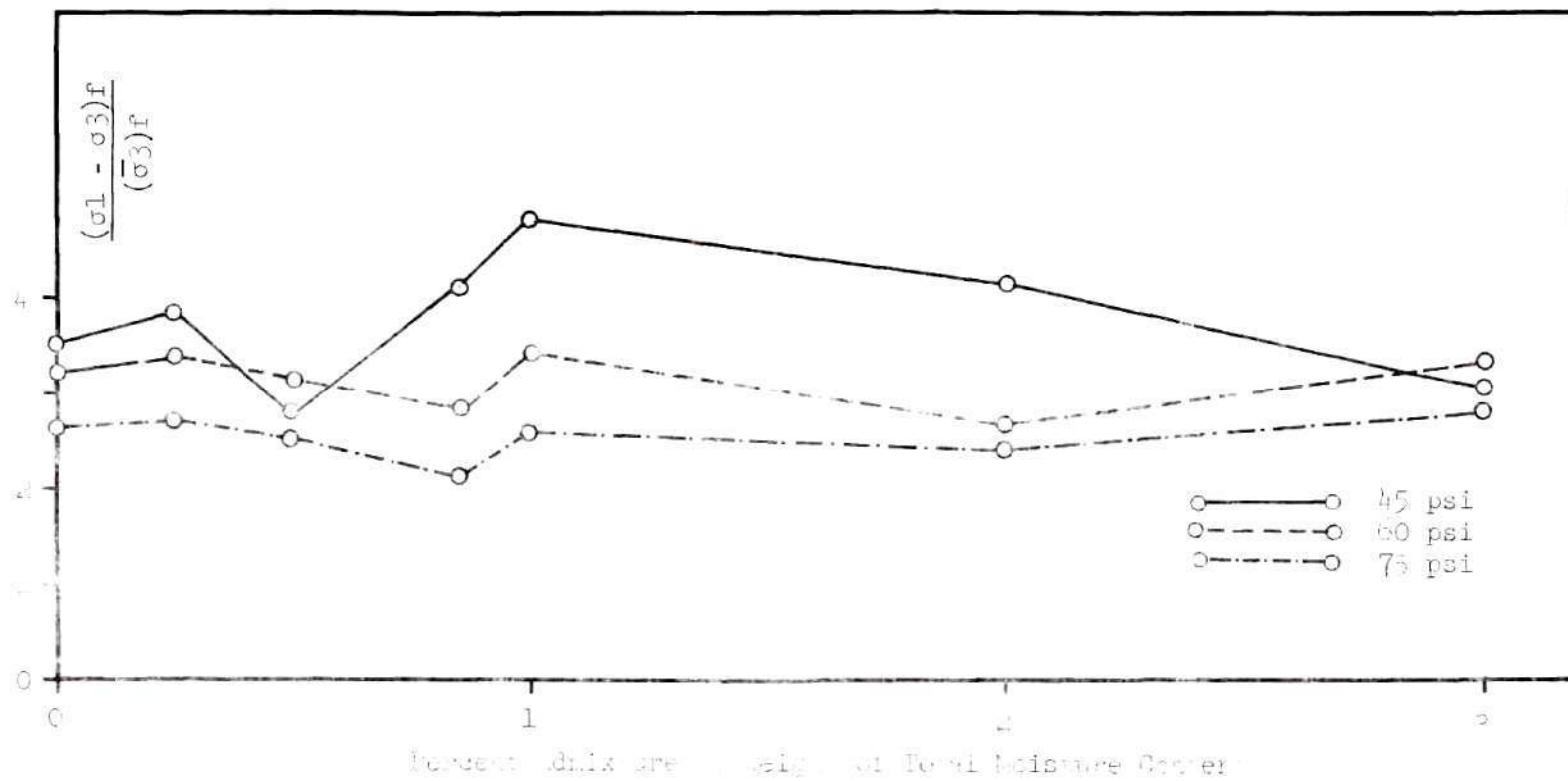


Figure 17. Relationship of $\frac{(\sigma_1 - \sigma_3)f}{(\bar{\sigma}_3)f}$ and Admixture Altrafol

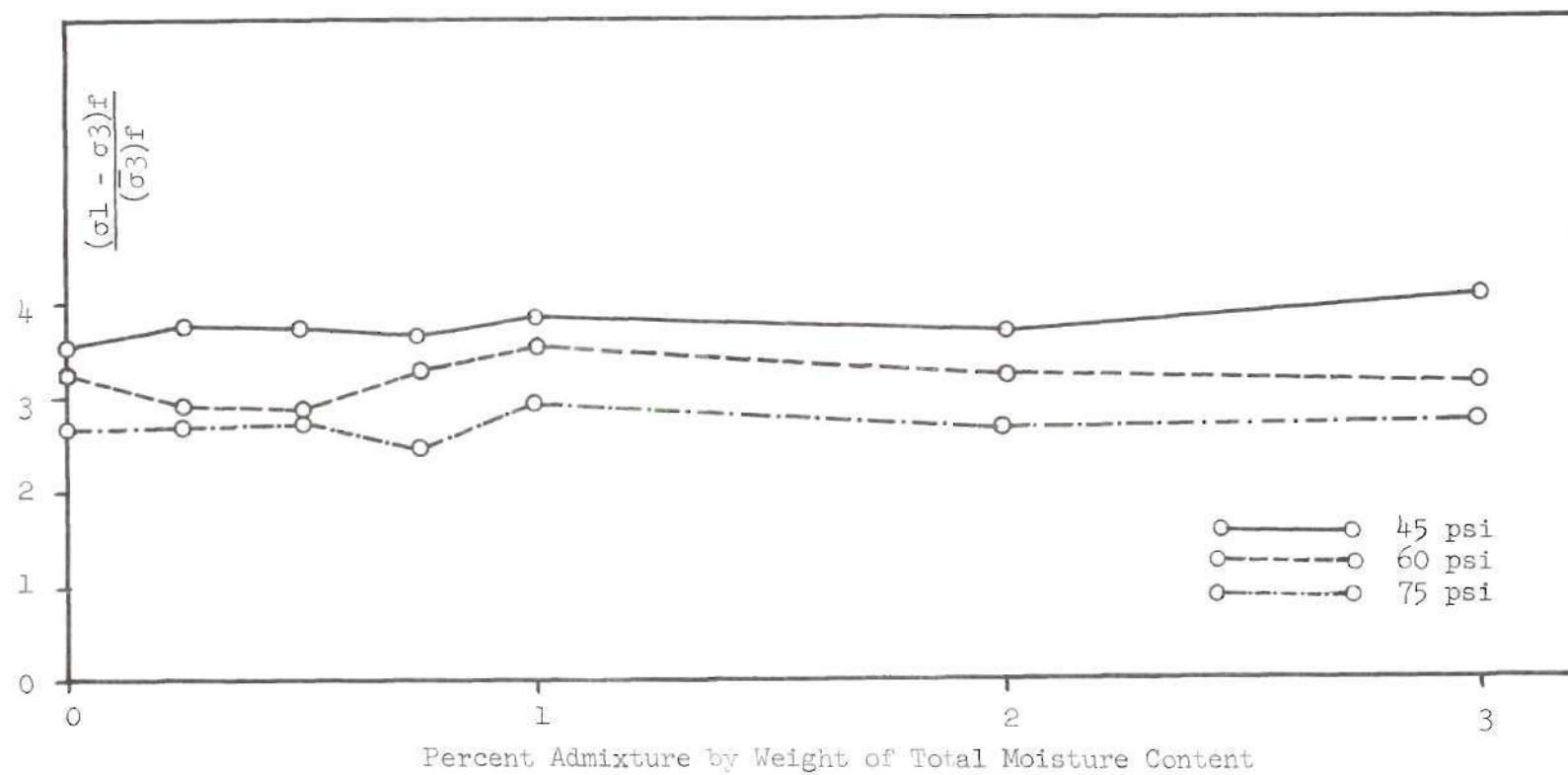


Figure 18. Relationship of $\frac{(\sigma_1 - \sigma_3)f}{(\sigma_3)f}$ and Admixture Naeconol Beads

changes at conditions other than optimum moisture and maximum density.

The effect of chemical on the shear strength parameters will be discussed separately.

The results obtained for the apparent cohesion intercept with increasing percentages of admixture seem more understandable than those obtained for the strength. Evaluation of Figure 19 shows that the apparent cohesion increases with increasing percentages of admixture, Tergitol TP-9. The maximum value is 58 percent higher than that corresponding to the untreated soil, and it occurs for a percent admixture of 1.1 percent. Further increase in the chemical concentration produces a decrease from the maximum in the apparent cohesion. For 3 percent admixture, the value is 27 percent higher than that for the untreated soil, and the slope of the curve indicates that further increase in chemical concentration decreases the apparent cohesion intercept.

Figure 20 shows that increasing percent admixture of polytergent LF-405 produces an increase in the apparent cohesion. The maximum value occurred at 1.2 percent concentration, and is 48 percent higher than that for the untreated soil. Further increase in chemical concentration produced a decrease from the maximum in apparent cohesion. The corresponding value for 3 percent concentration resulted 31 percent lower than that for the untreated soil and the slope of the curve indicates that lower values may occur for greater chemical concentration.

Evaluation of Figure 21 shows that increasing percent admixture of alkonol B between 0 and 1 percent causes increases in the apparent cohesion. The maximum value corresponds to 1 percent admixture and it is 100 percent higher than that for the untreated soil. Percentages

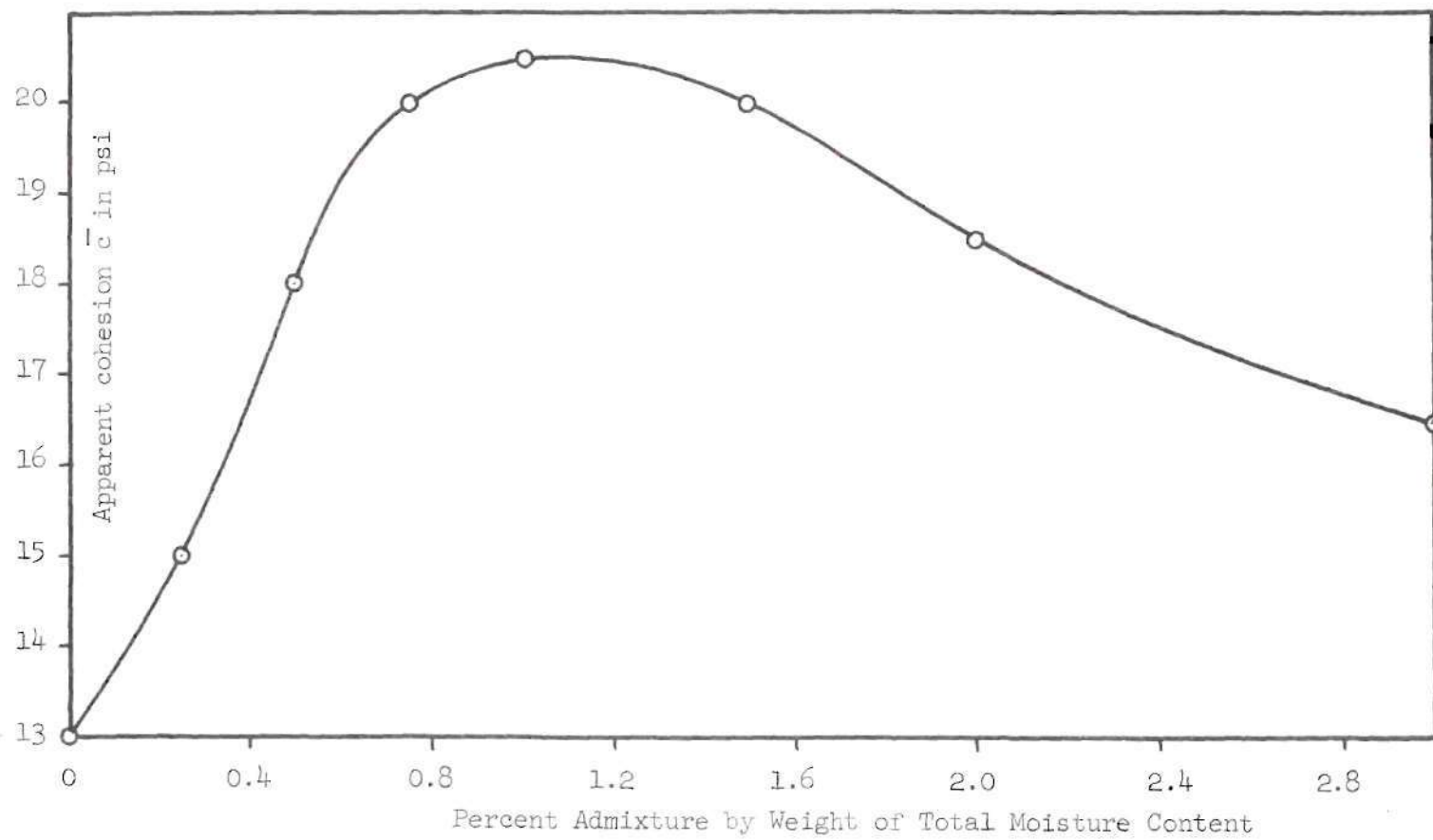


Figure 19. Relationship of Apparent Cohesion and Admixture Tergitol TP-9

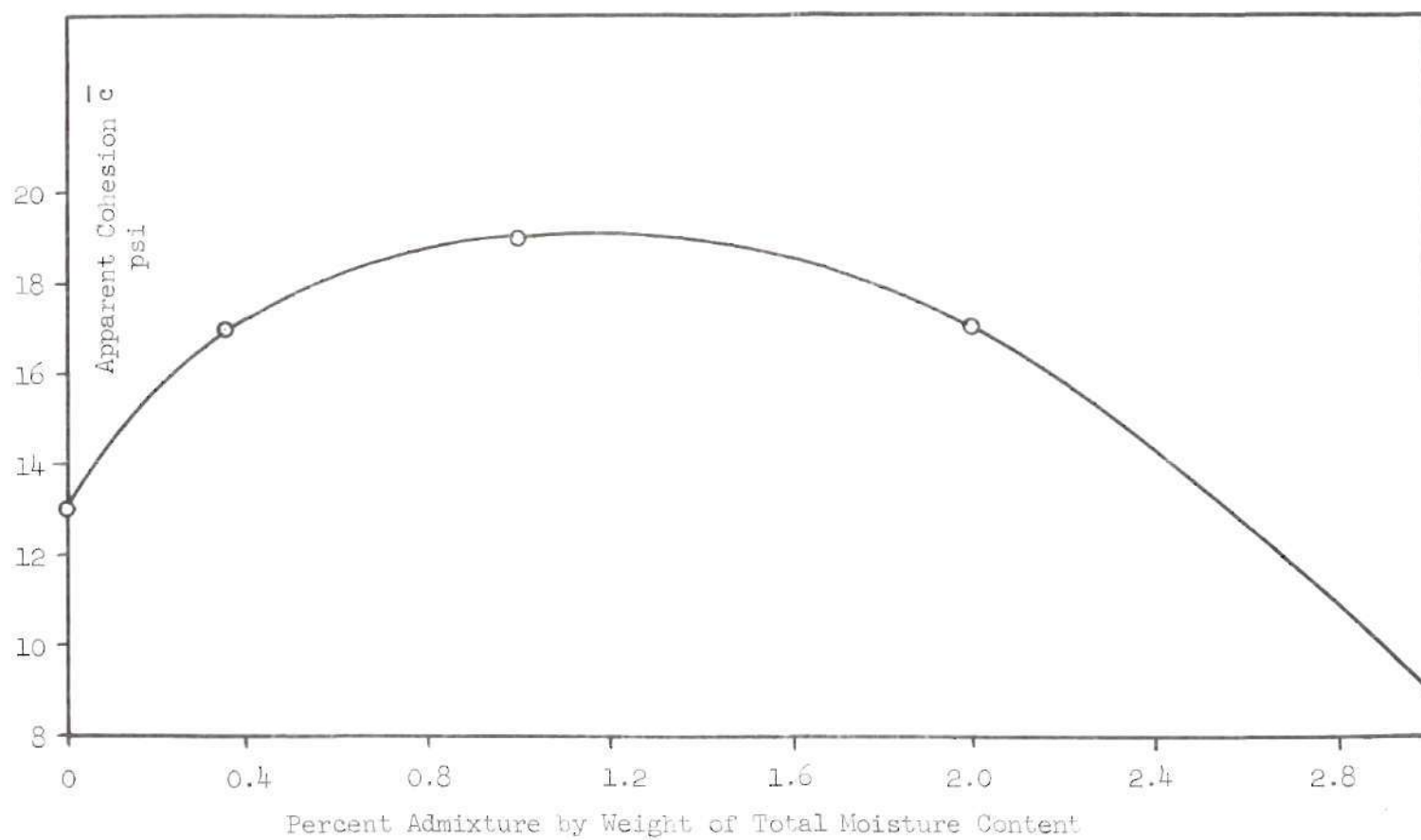


Figure 20. Relationship of Apparent Cohesion and Admixture Polytergent LF-405

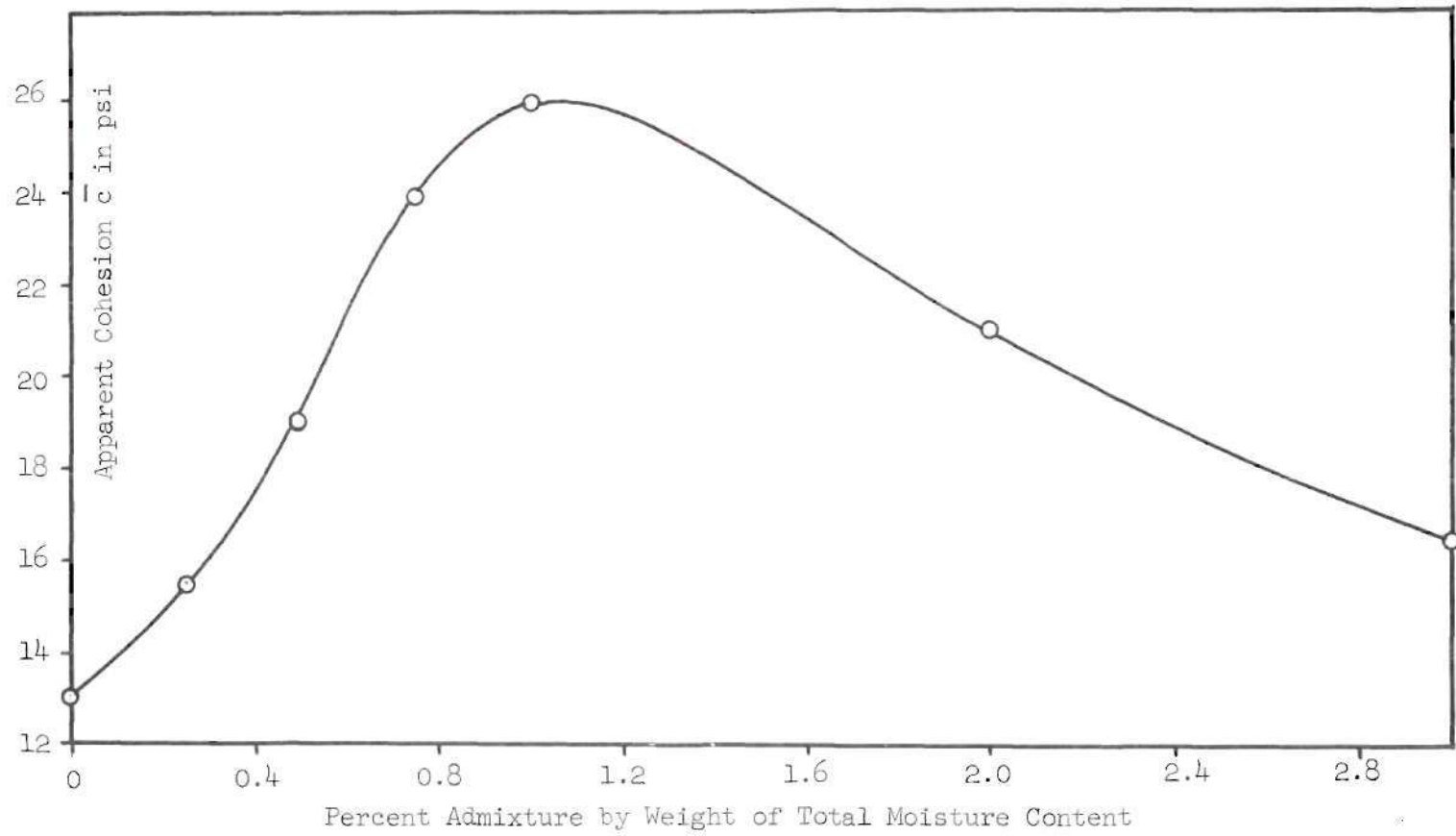


Figure 21. Relationship of Apparent Cohesion and Admixture Alkanol B

above 1 percent produce a decrease from the maximum in the apparent cohesion. The lowest value recorded corresponded to 3 percent concentration, being 27 percent higher than that for the untreated soil.

Figure 22 shows that the apparent cohesion is increased for percentages of admixture nacconol beads ranging between 0 and 1.0 percent. The maximum value corresponds to 1 percent admixture, resulted in 59 percent higher cohesion than that for the untreated soil. Further increases in chemical concentration indicates that the cohesion is lowered, compared to the maximum. The lowest value recorded corresponded to 3 percent admixture and is only 15 percent higher than that for the untreated soil.

Evaluation of Figures 19, 20, 21 and 22 indicates that the greatest effect on the cohesion is produced by the chemicals of the anionic group. These chemicals are water soluble and when added to the soil reduce the surface tension of the water soil structure. The effect of the chemical seems to decrease the electrostatic repulsive forces, or to act as molecular bridges between particles, thus facilitating interparticle true attraction or cohesion.

Evaluation of Figures 23, 24, 25 and 26 shows that the apparent angle of internal friction decreases with increasing percentages of admixture up to 1.5 percent. The minimum values occurred at percent of admixture ranging between 1.0 and 1.5. As the percentage of admixture was increased beyond 1.5 percent, the apparent angle of internal friction increased, and for a 3.0 percent admixture the apparent angle of internal friction was approximately equal to that of the untreated soil.

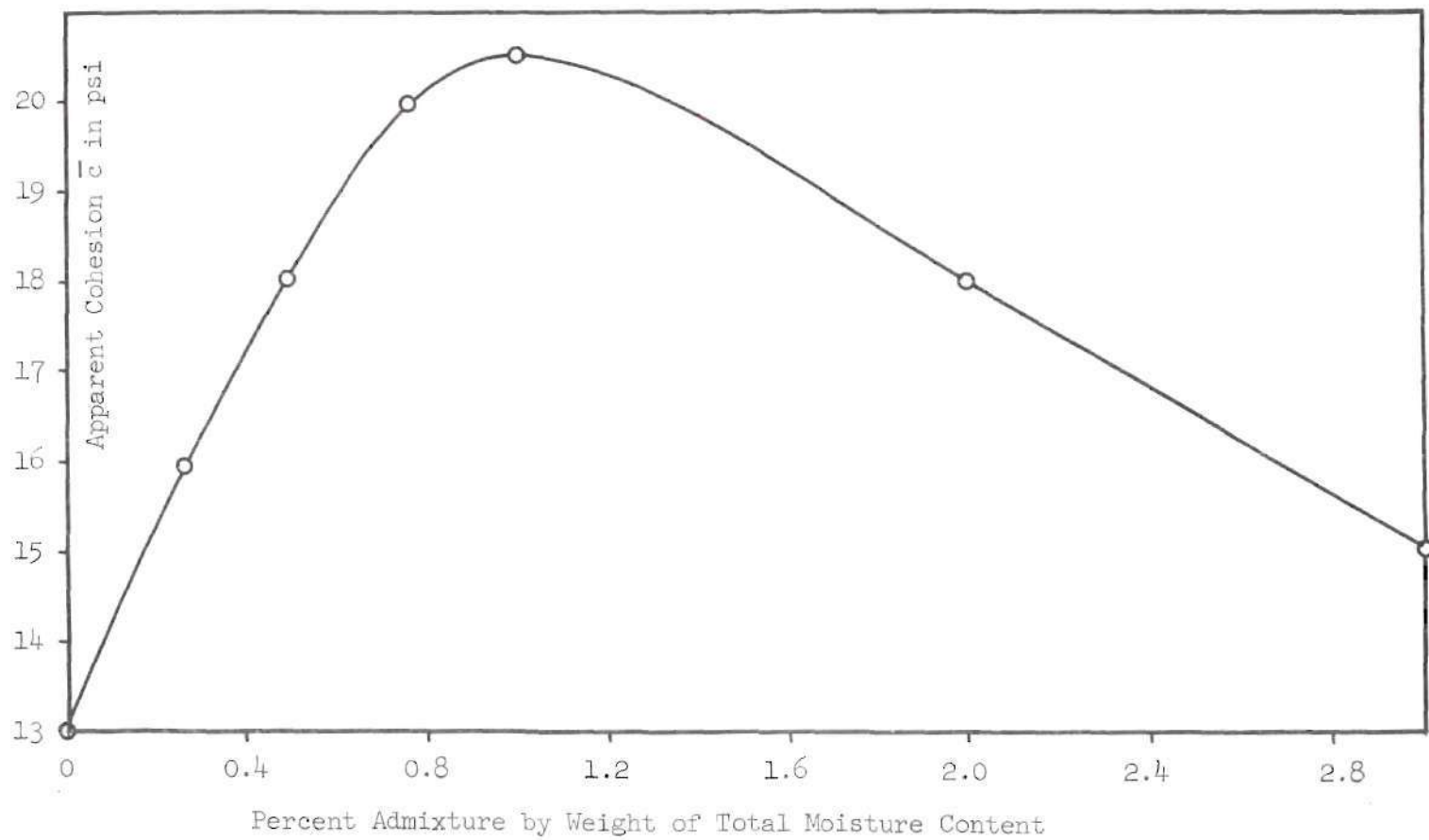


Figure 22. Relationship of Apparent Cohesion and Admixture Nacconol Beads

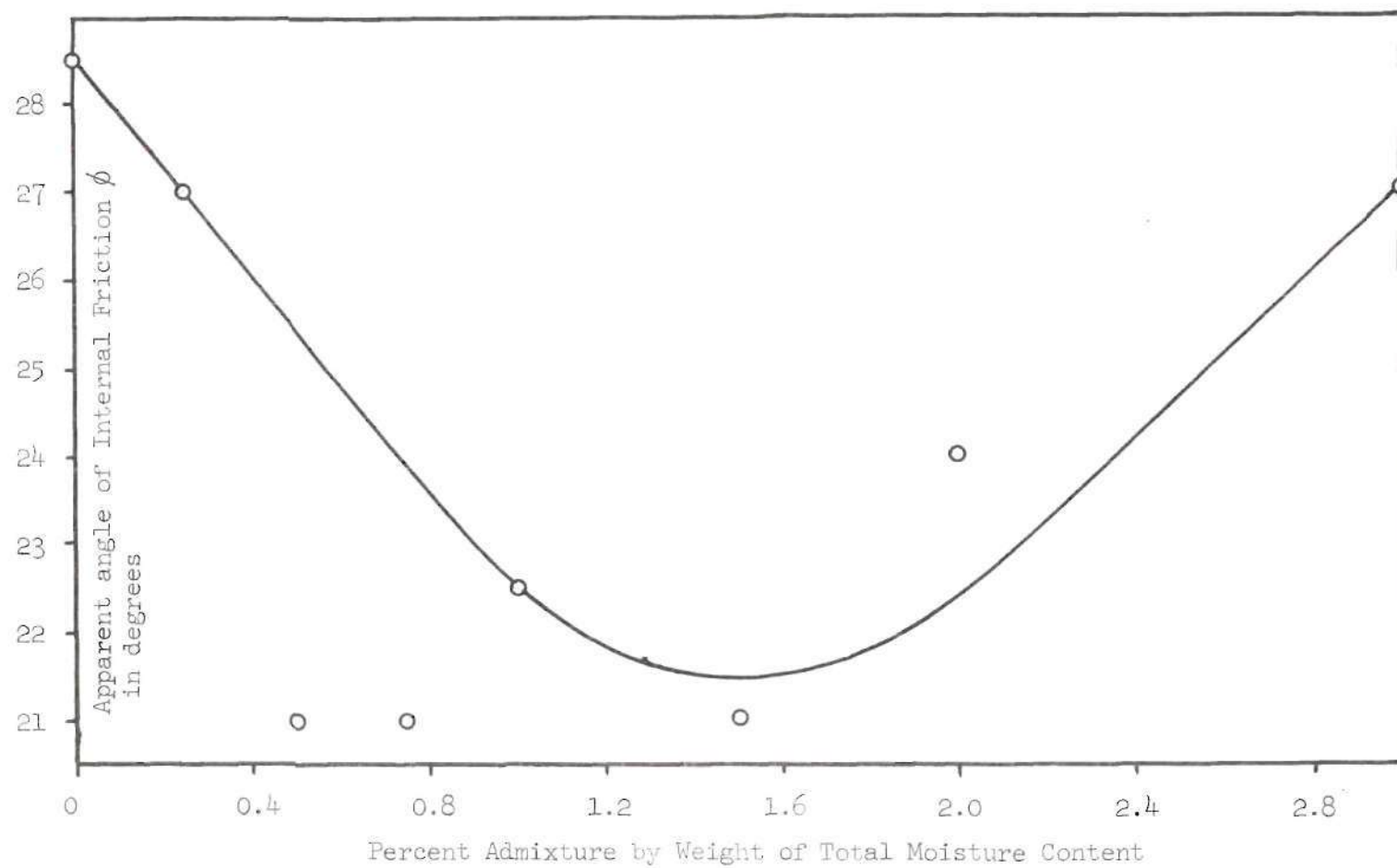


Figure 23. Relationship of Apparent Angle of Internal Friction and Admixture Tergitol TP-9

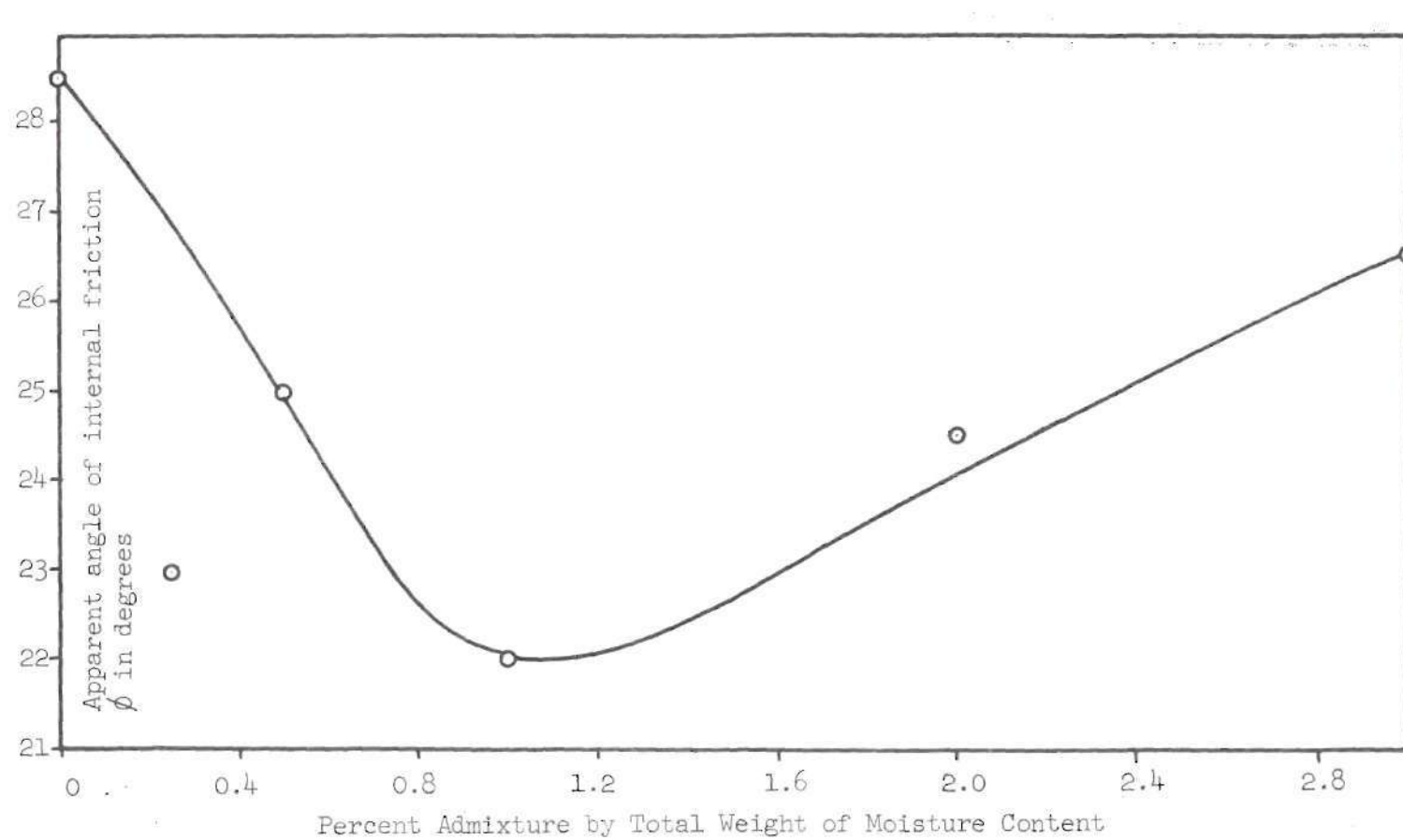


Figure 24. Relationship of Apparent Angle of Internal Friction and Admixture Polytergent LF-405

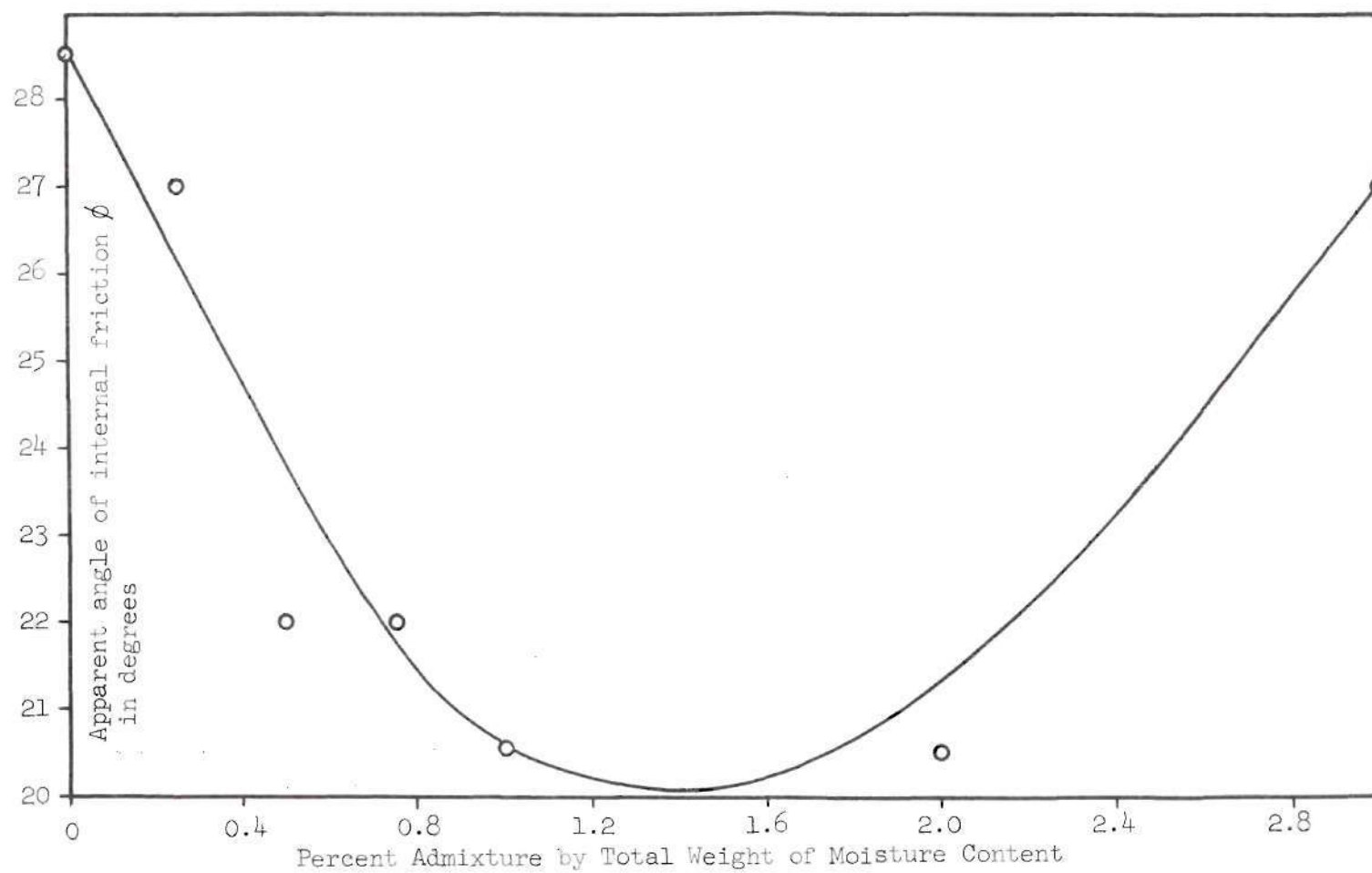


Figure 25. Relationship of Apparent Angle of Internal Friction and Admixture Alkanol B.

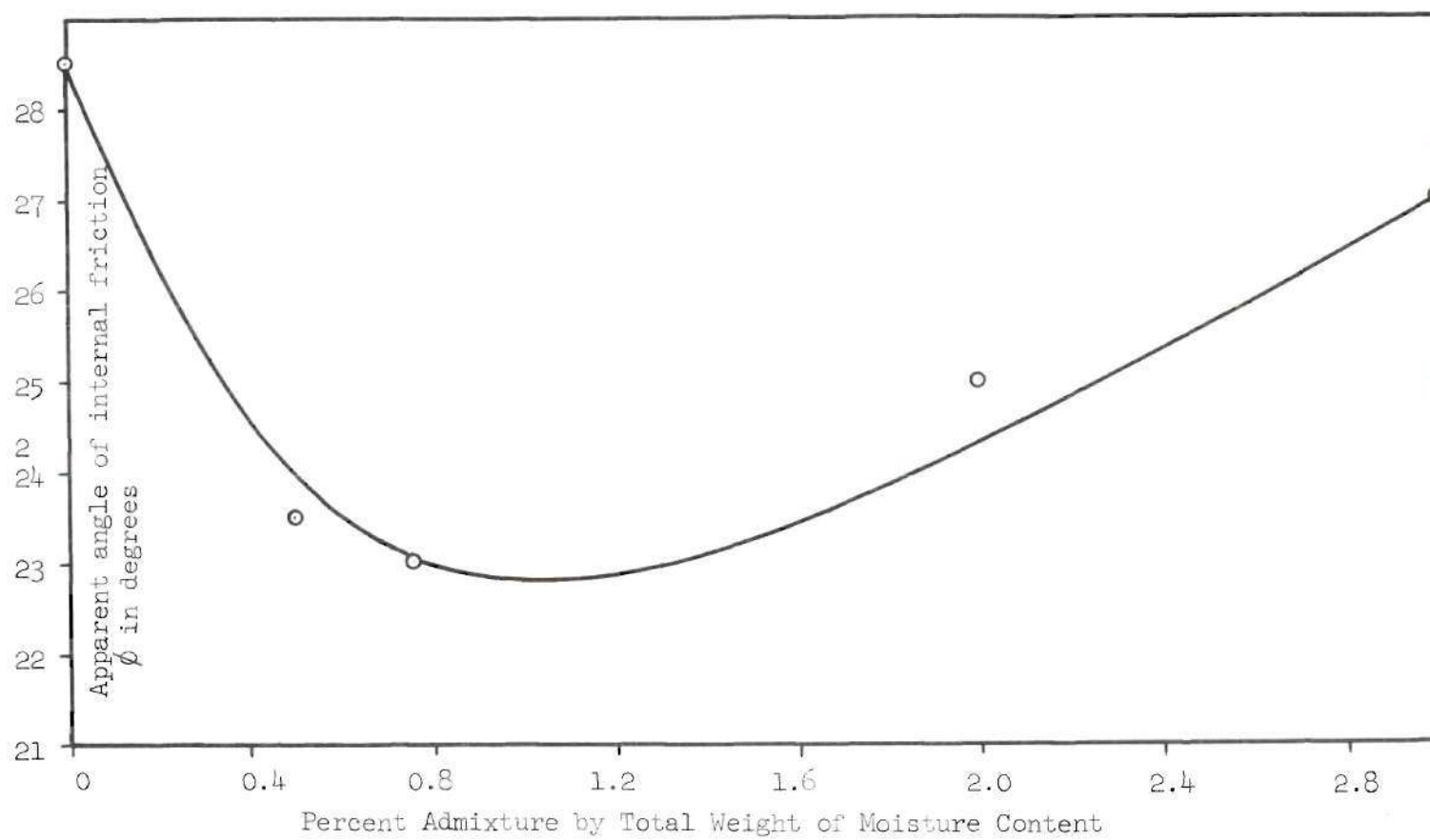


Figure 26. Relationship of Apparent Angle of Internal Friction and Admixture Nacconol Beads

Pore Water Pressure

Evaluation of all the graphs obtained for the pore water pressure shows it decreased during the test. This behavior is typical of overconsolidated, or compacted cohesive soils, and can be explained by the soil structure theory. At the beginning of the test, the voids are partially filled with water, and the pore pressure is slightly negative due to capillary tension. Only limited literature is available to explain the behavior of partly saturated soils, and the factors that govern the pore water pressure are not completely known.

Pore Water Pressure - Percent Admixture

Evaluation of figures 27, 28, 29 and 30 shows small changes in pore water pressure for increasing percentages of admixture. These changes vary with the all around pressure $\bar{\sigma}_3$. Discrepancies in the results are difficult to explain because the tests were performed under different conditions.

In general, the two chemicals belonging to the nonionic group (Tergitol TP-9 and Polytergent LF-405) present similar results. The pore water pressure increases between 0 and one percent admixture, then decreases between 1 and 2 percent and finally it increases again between 2 and 3 percent admixture. The behavior of the soil is typical of overconsolidated or compacted cohesive soils, and with the information obtained, the effect of the chemical on the pore water pressure could not be determined.

The results for the two chemicals of the anionic group do not follow the same path. The behavior of the soil treated with alkanol B

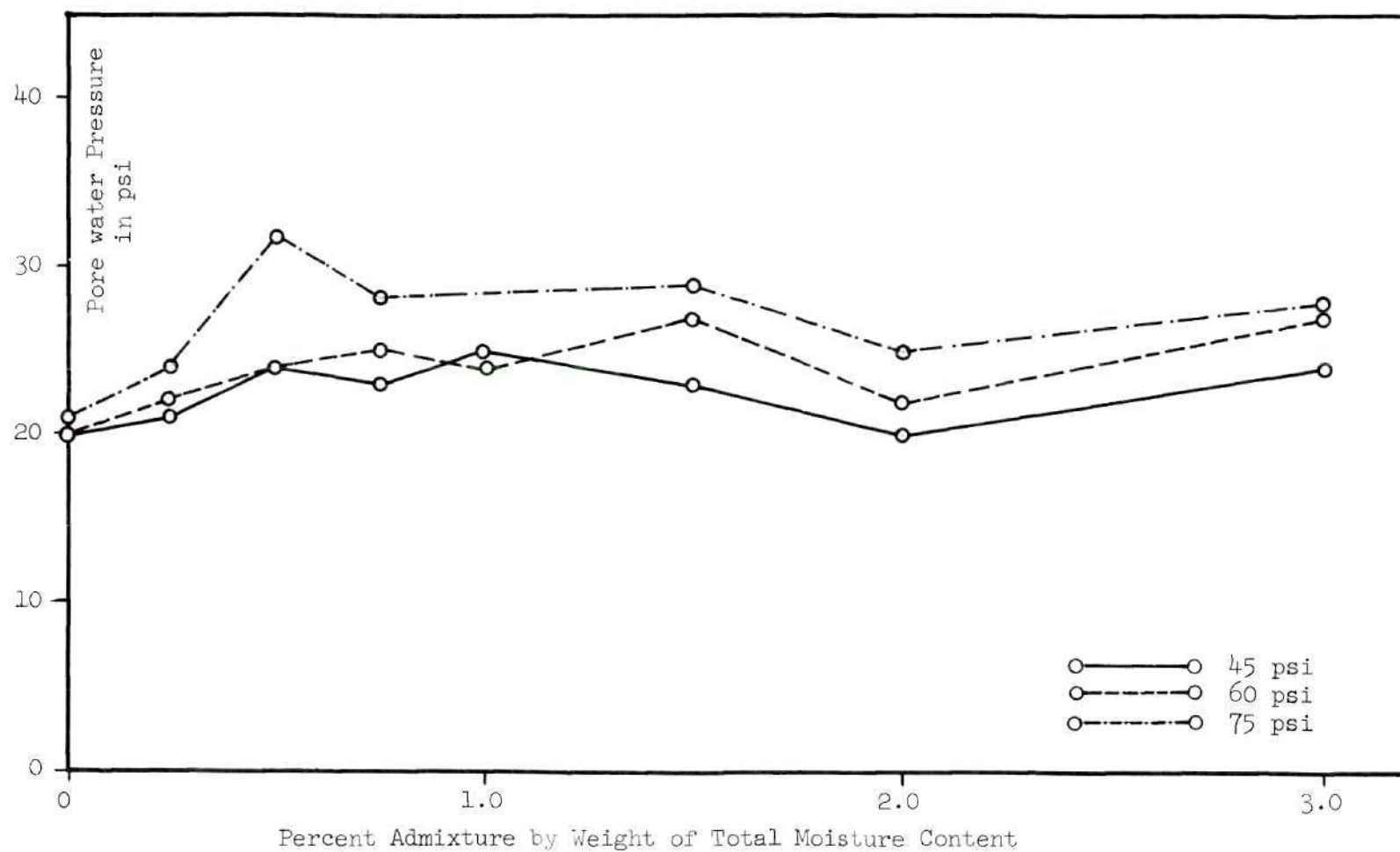


Figure 27. Relationship of Pore Water Pressure and Admixture Tergitol TP-9

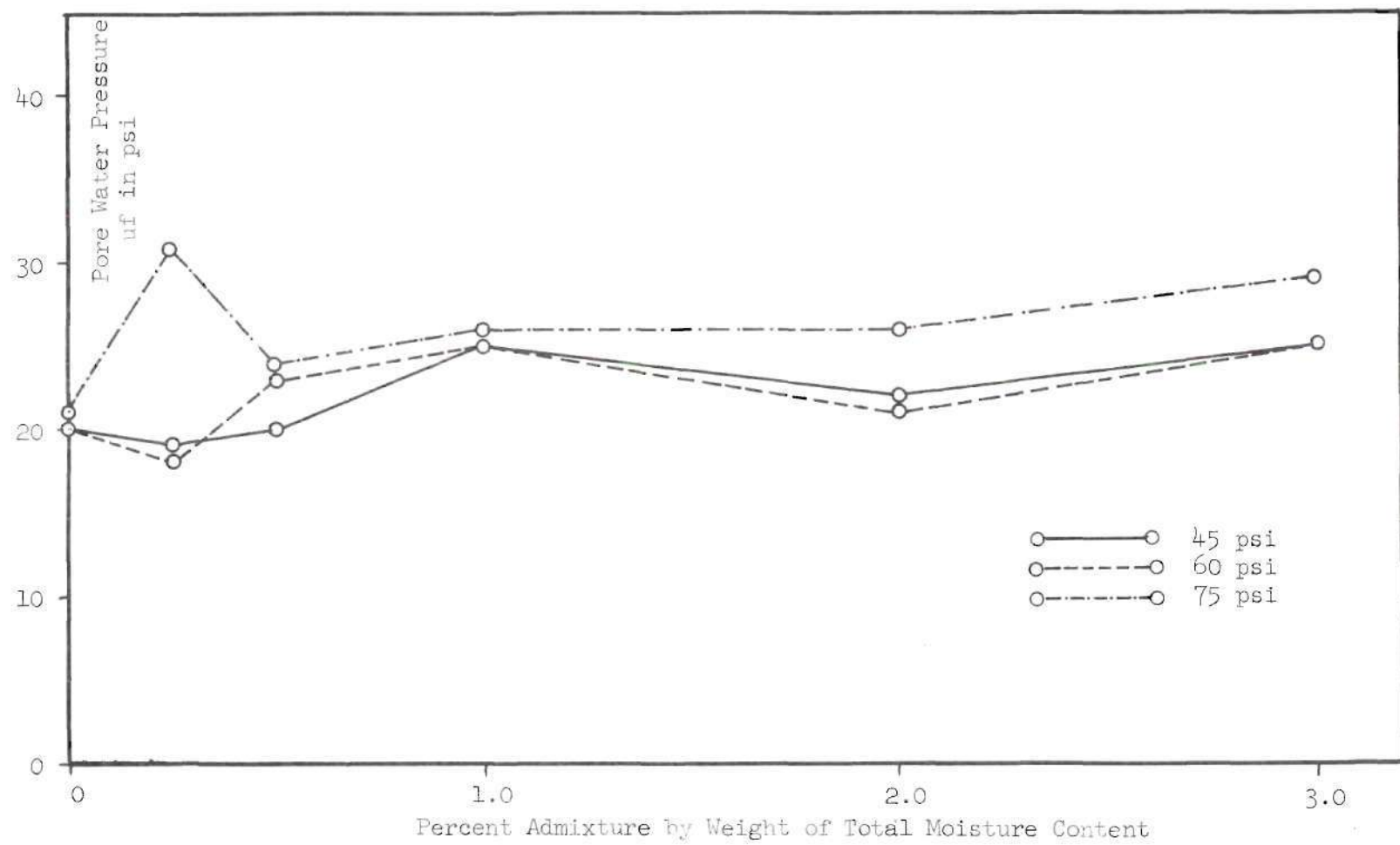


Figure 28. Relationship of Pore Water Pressure and Admixture Polytergent LF-405

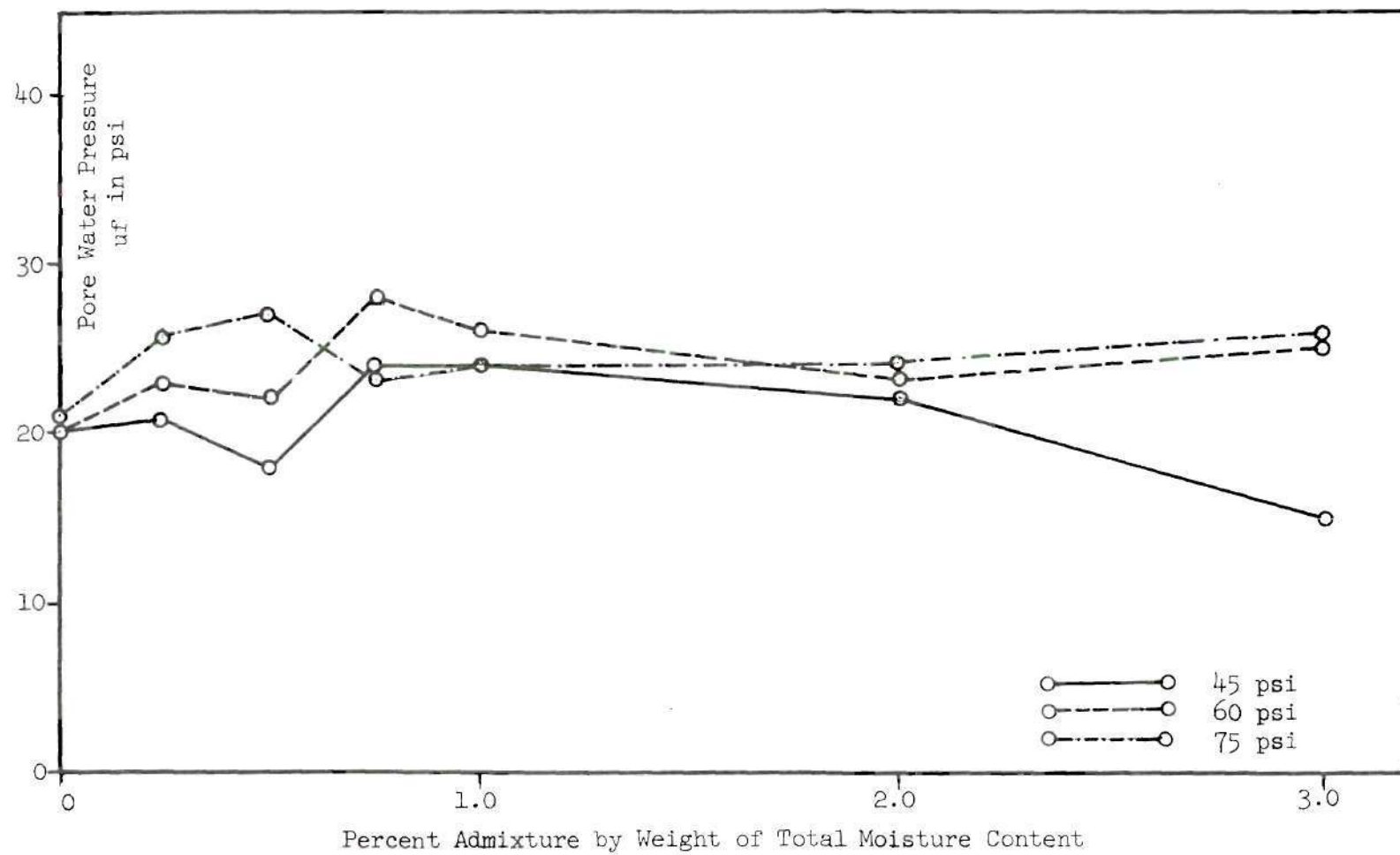


Figure 29. Relationship of Pore Water Pressure and Admixture Alkanol B

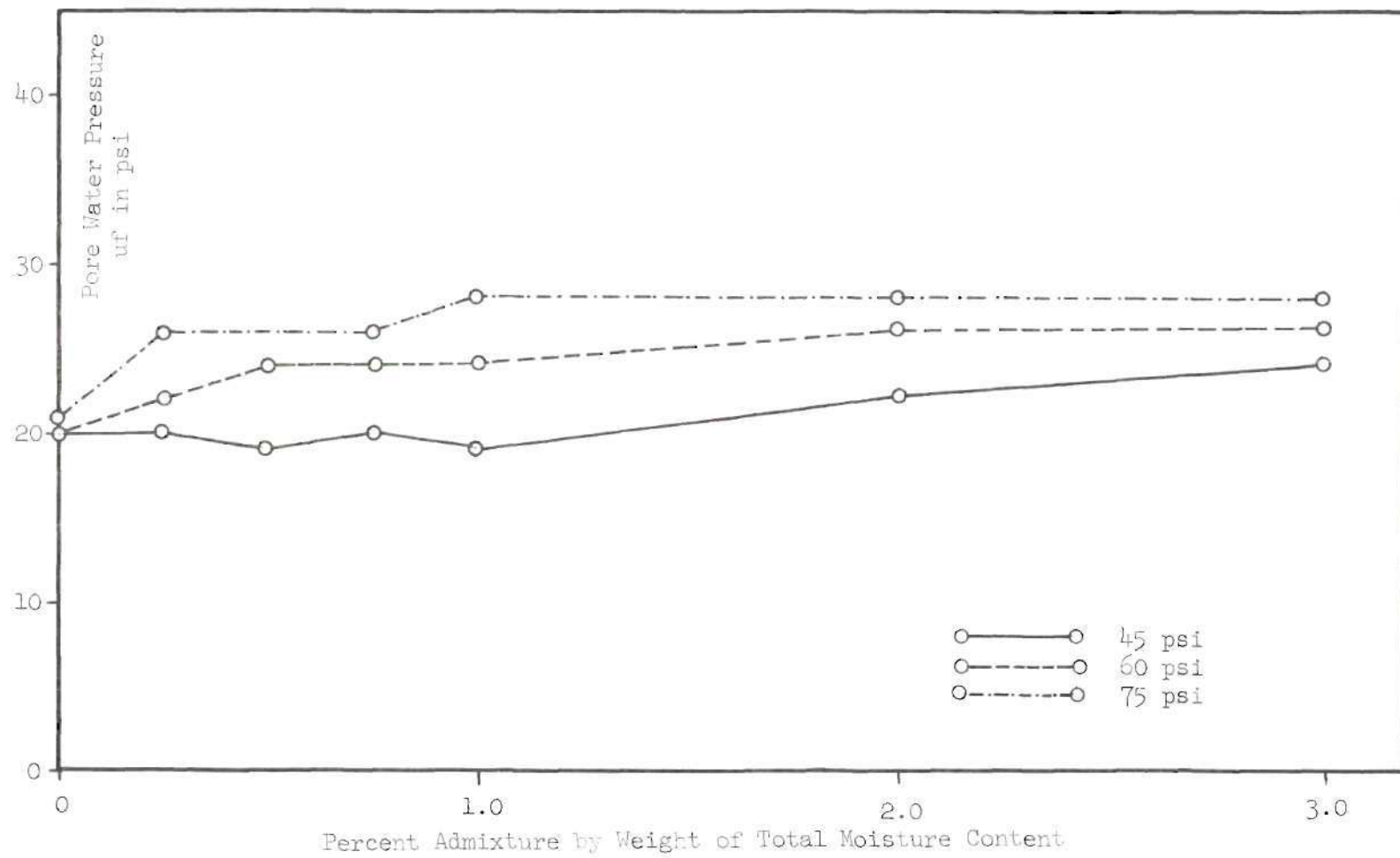


Figure 30. Relationship of Pore Water Pressure and Admixture Nacconol Beads

seems to follow the same path of that obtained from nonionic chemicals, but discrepancies in the results make it difficult to establish this relationship.

In the soil samples treated with nacconol Beads, the pore water pressure increases with increases in chemical concentration. The effect seems to be greater for low overconsolidation ratios.

Pore Water Pressure Parameter B

The two tests to determine the pore water pressure parameter B were explained in the procedure. The procedure followed in Method II fits better with that followed during the testing program. The results of these tests are shown in Figures 13 and 14. It should be pointed out that this value is not representative for all the tests because the conditions during the testing program varied in a wide range. Table 6 shows the values obtained for both tests.

Pore Water Pressure Parameter \bar{A}_f

In table 5 can be found the values obtained for the pore water pressure parameter \bar{A}_f . It is difficult to define a relationship between \bar{A}_f and percentages of admixture used, due to discrepancies in the results.

It was found that the pore water pressure parameter \bar{A}_f decreases when the overconsolidation pressure is increased. This agrees with previous investigation by Bishop and Henkel (9).

CHAPTER V

CONCLUSIONS

The following conclusions can be obtained from the research:

(1) The ratio, $\frac{(\sigma_1 - \sigma_3)_f}{(\sigma_3)_f}$ varied only slightly with increasing percentages of admixture for all admixtures.

(2) The pore water pressure varied only slightly with increasing percentages of admixtures for all admixtures.

(3) An increase in apparent cohesion was obtained for all admixtures. The maximum effect was produced by the surfactants belonging to the anionic type.

A. The maximum increase in apparent cohesion resulted for percentages of admixture of 1.0 percent.

B. Higher percentages of admixture caused a diminishing rate of increase in cohesion.

(4) The apparent angle of internal friction was affected by the addition of all surfactants used.

A. The apparent angle of internal friction decrease for percentages of admixture between 0 and 1.5 percent.

B. Percentages of admixture higher than 1.5 percent increased the apparent angle of internal friction.

CHAPTER VI

RECOMMENDATIONS

From this research, several recommendations can be suggested for further study. These are:

- (1) An evaluation of the effect of surface active agents at different moisture contents.
- (2) A determination of the effect of surfactants with curing time on the effective stresses.
- (3) An evaluation of the long term strength for soils treated with surface active agents.
- (4) A study of the effect of surfactants on the permeability of residual soils.

APPENDIX

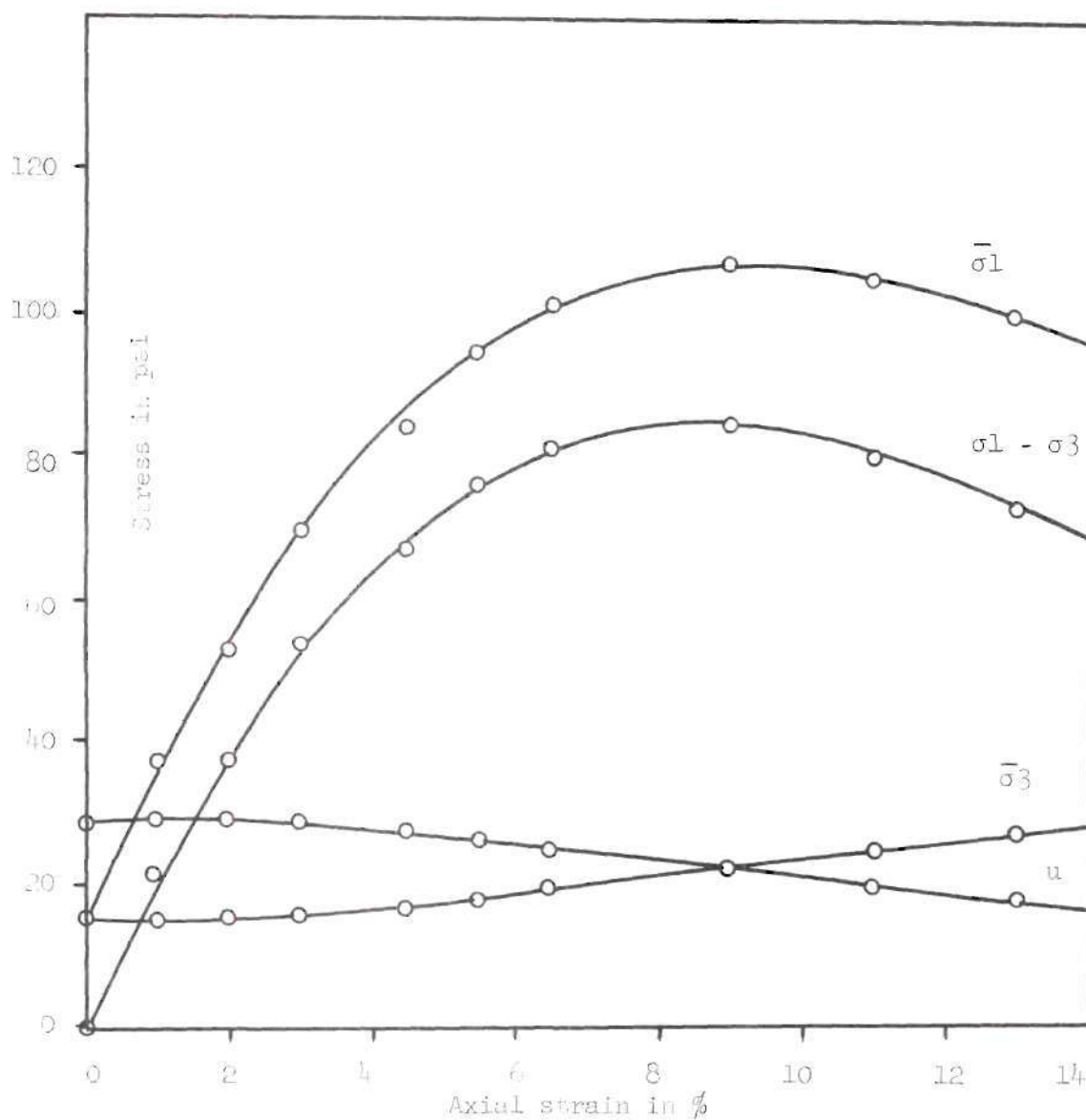


Figure 31. Triaxial Compression Test, Admixture: Tergitol TP-9, Ceresol Admixture: 0.25, All around Pressure: 45 psi

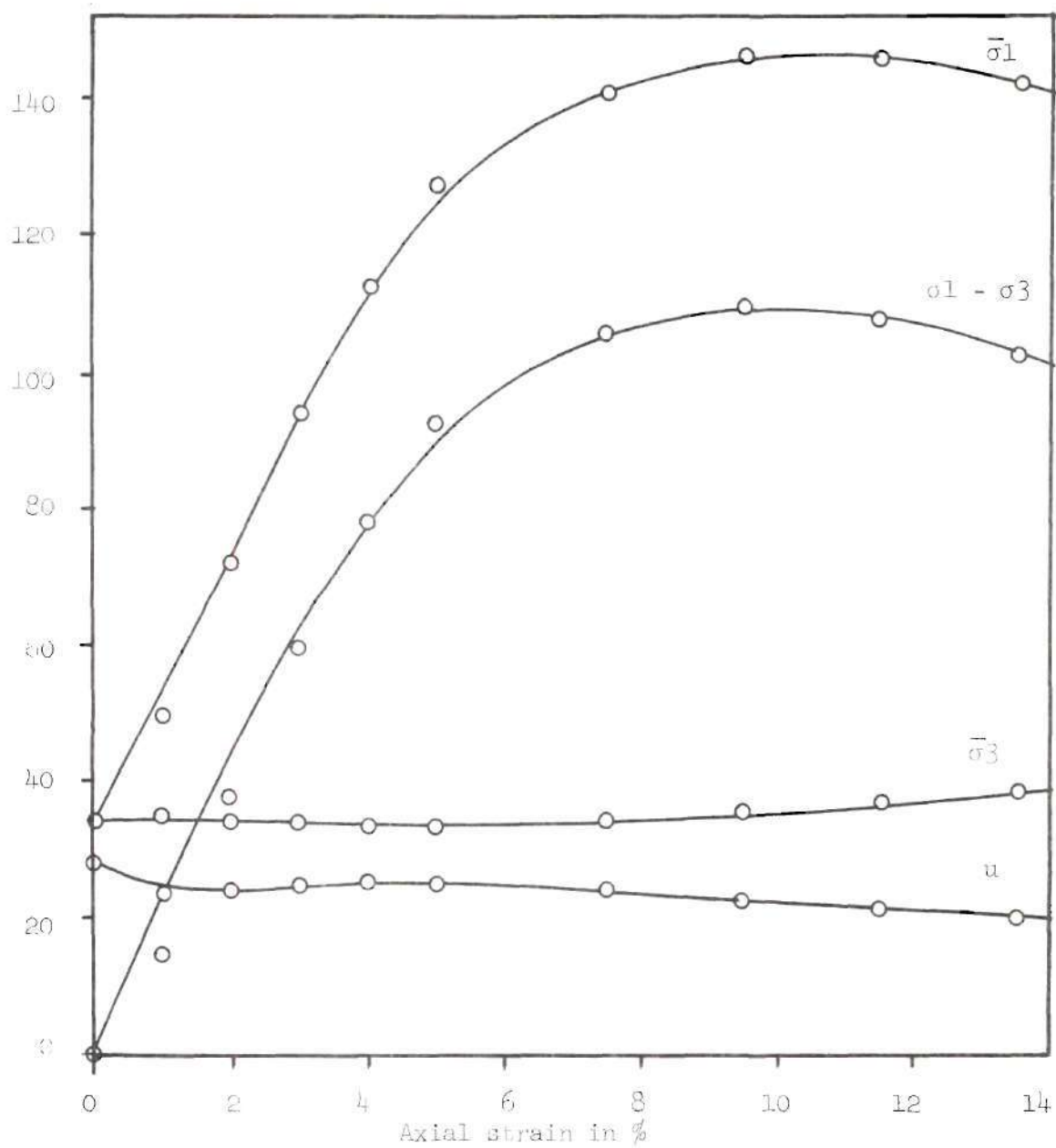


Figure 32. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 0.25
 All around Pressure: 60 psi

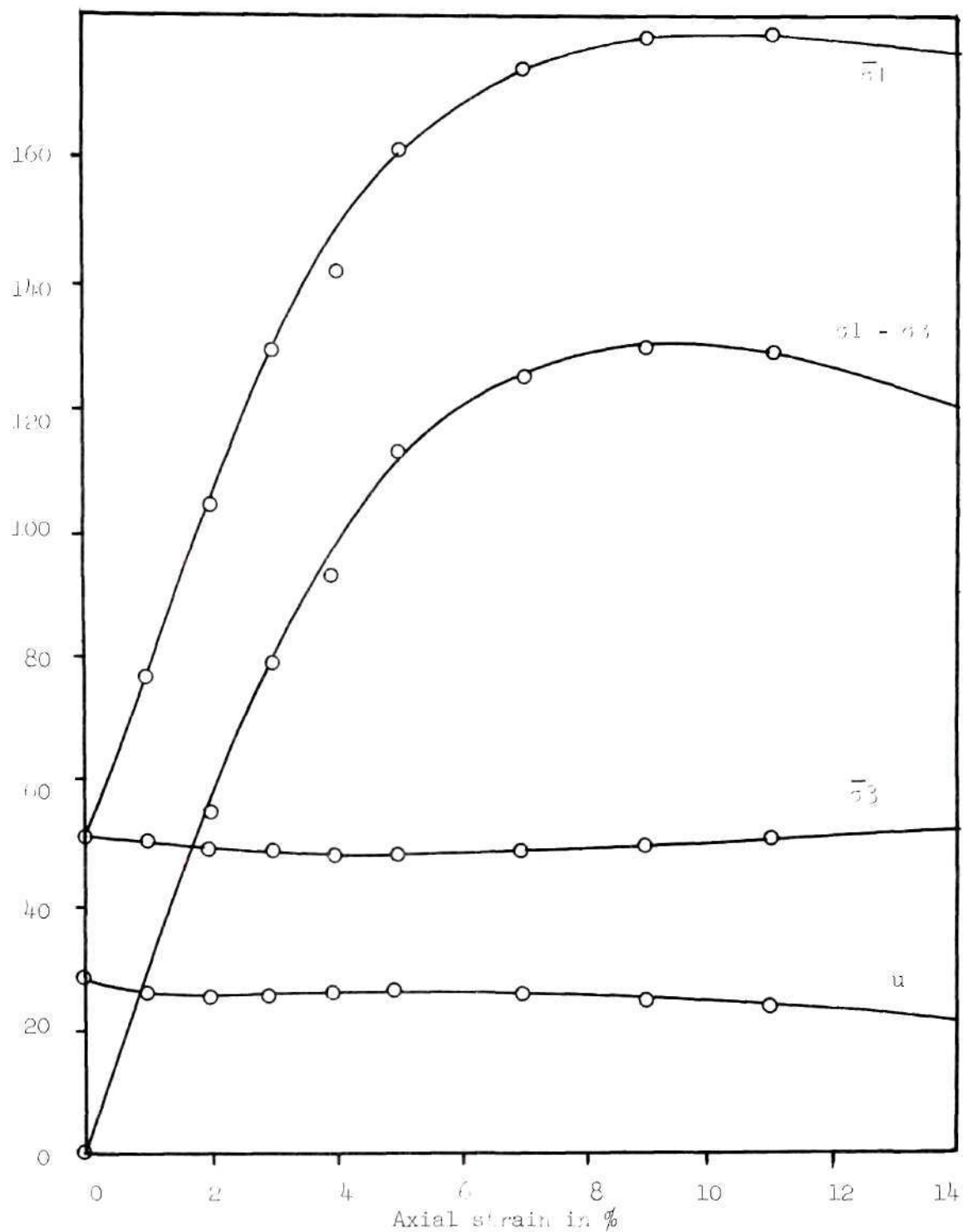


Figure 33. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 0.25
 All around Pressure: 75 psi

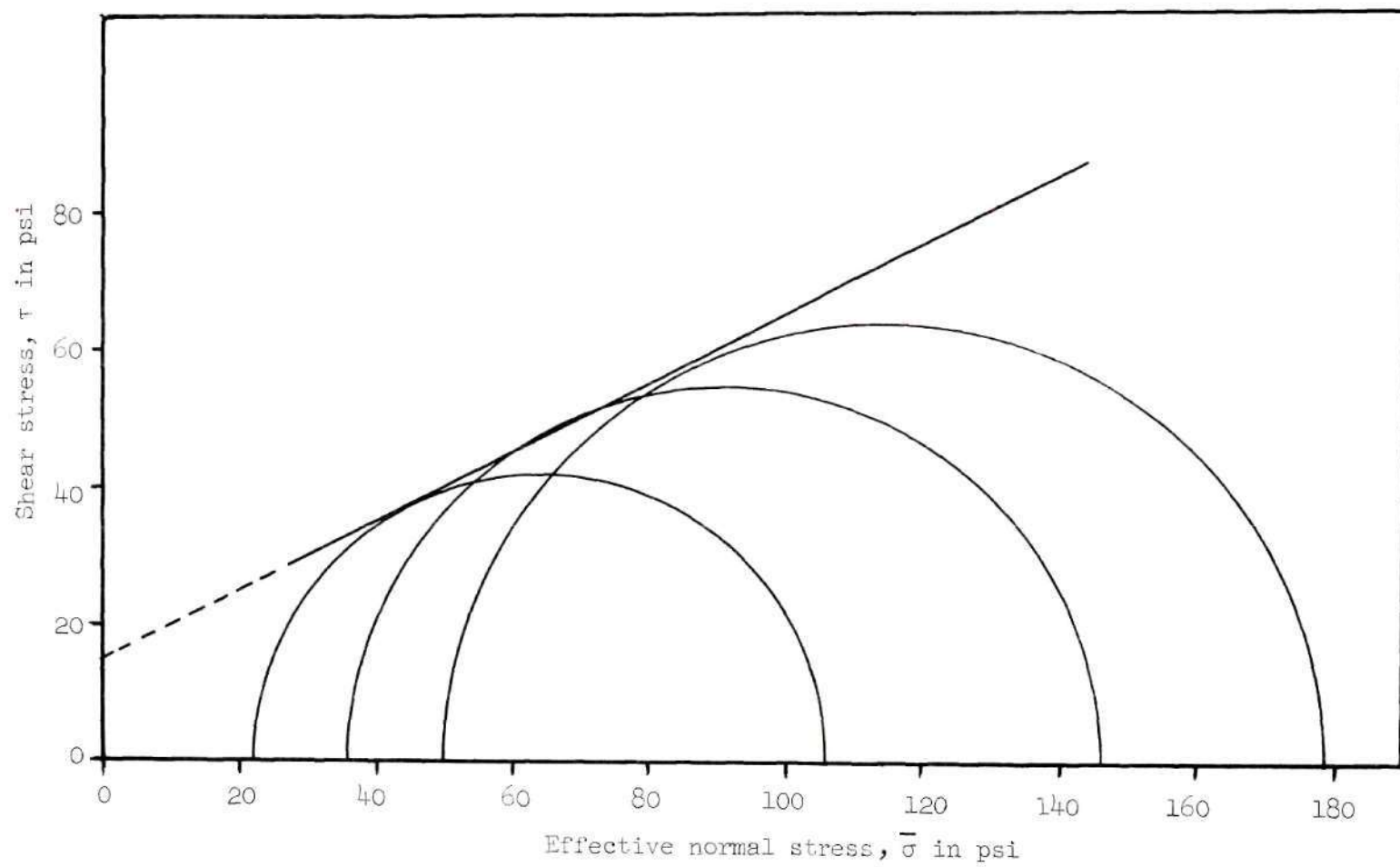


Figure 34. Mohr Circles
 Admixture: Tergitol TP-9
 Percent Admixture: 0.25

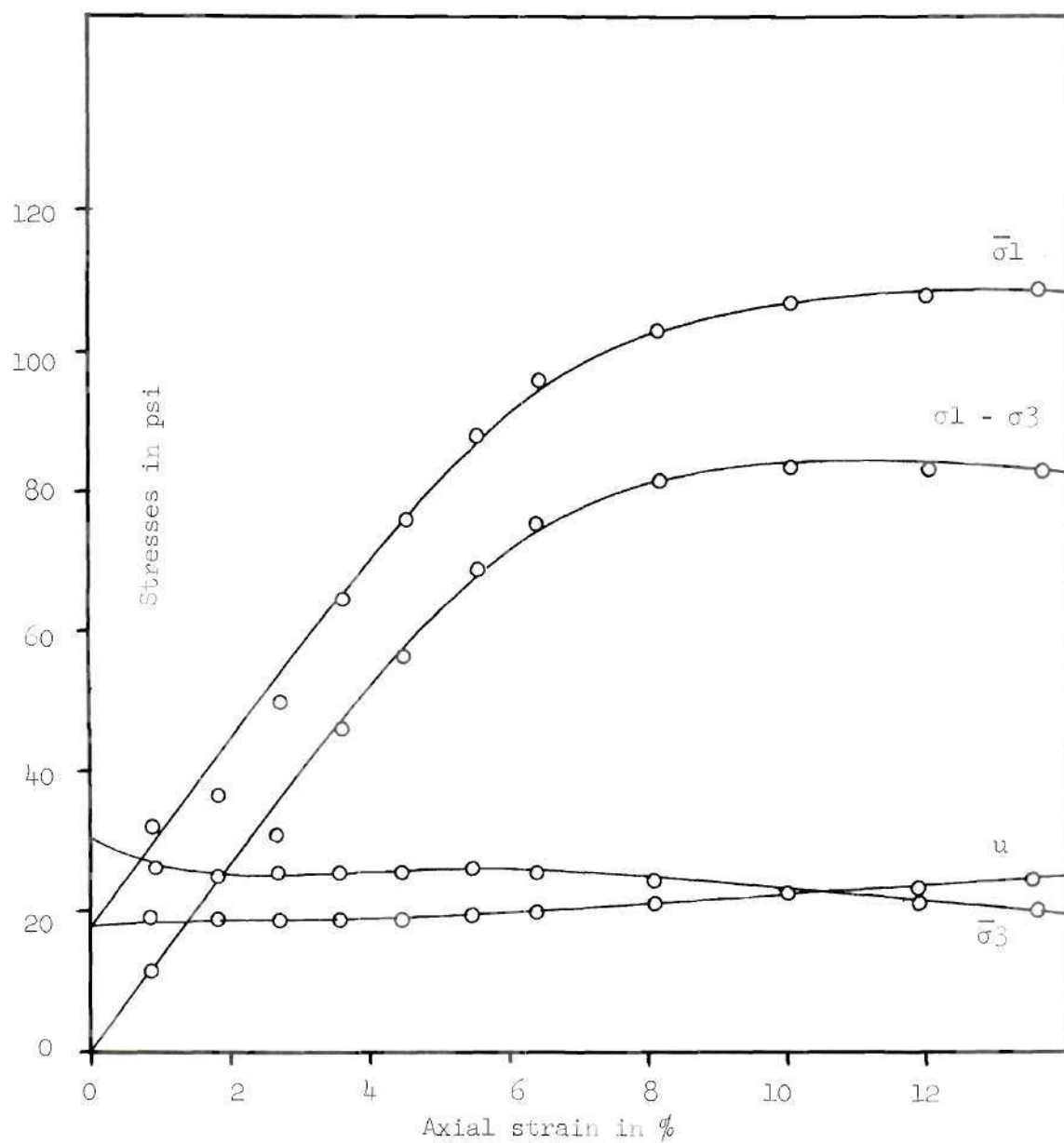


Figure 35. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 0.5
 All around Pressure: 45 psi

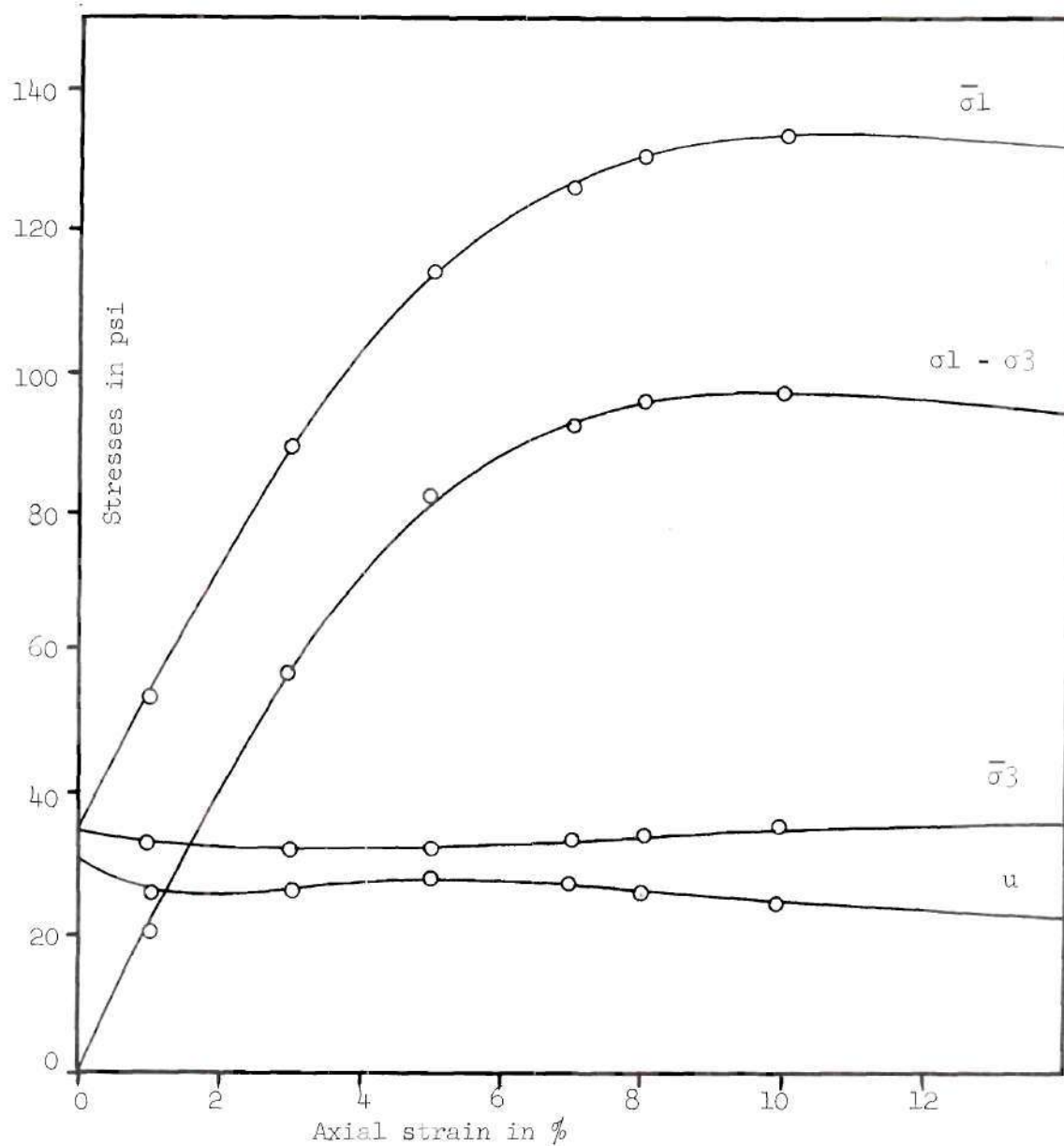


Figure 36. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 0.5
 All around Pressure: 60 psi

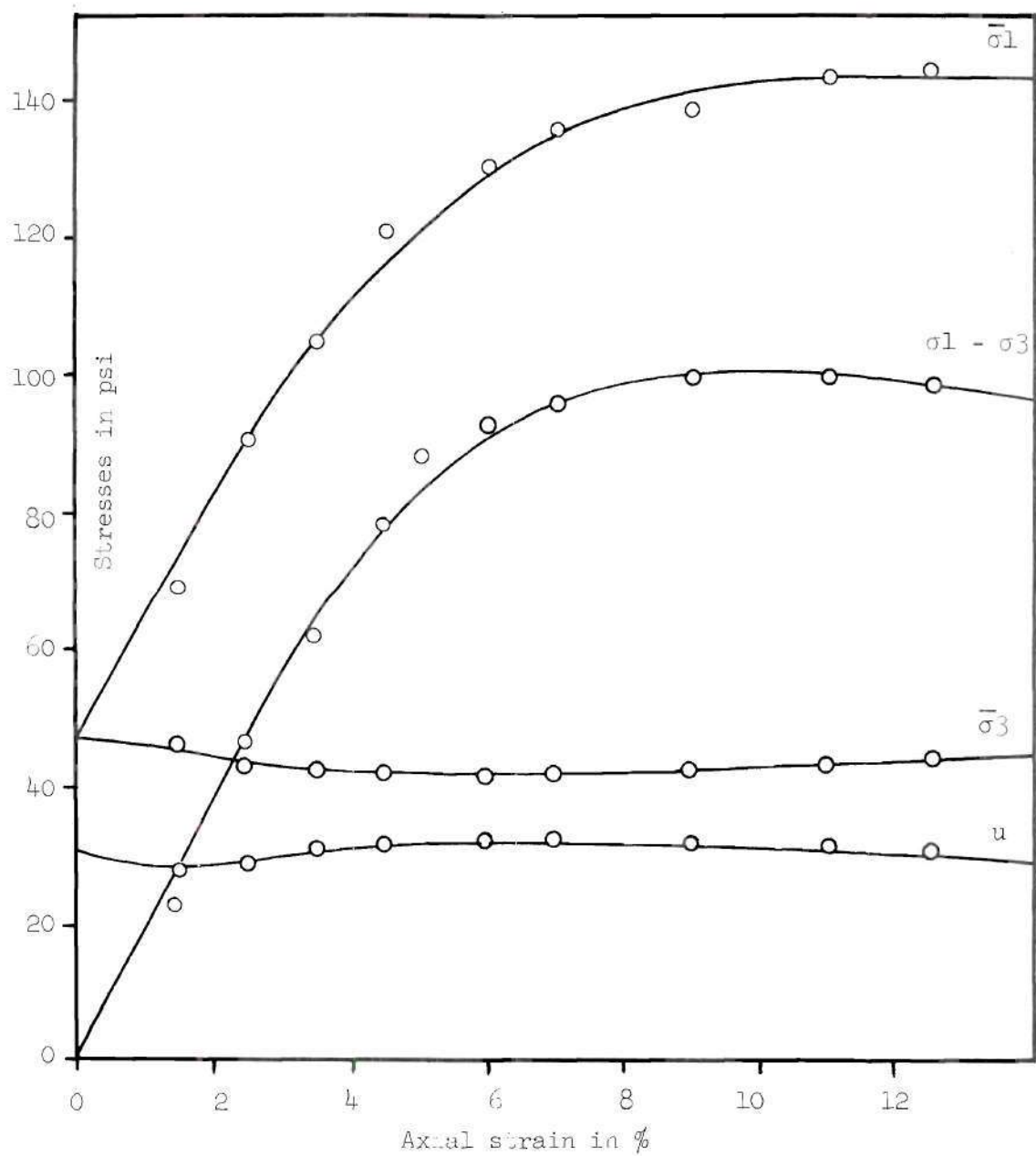


Figure 37. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 0.5
 All round Pressure: 75 psi

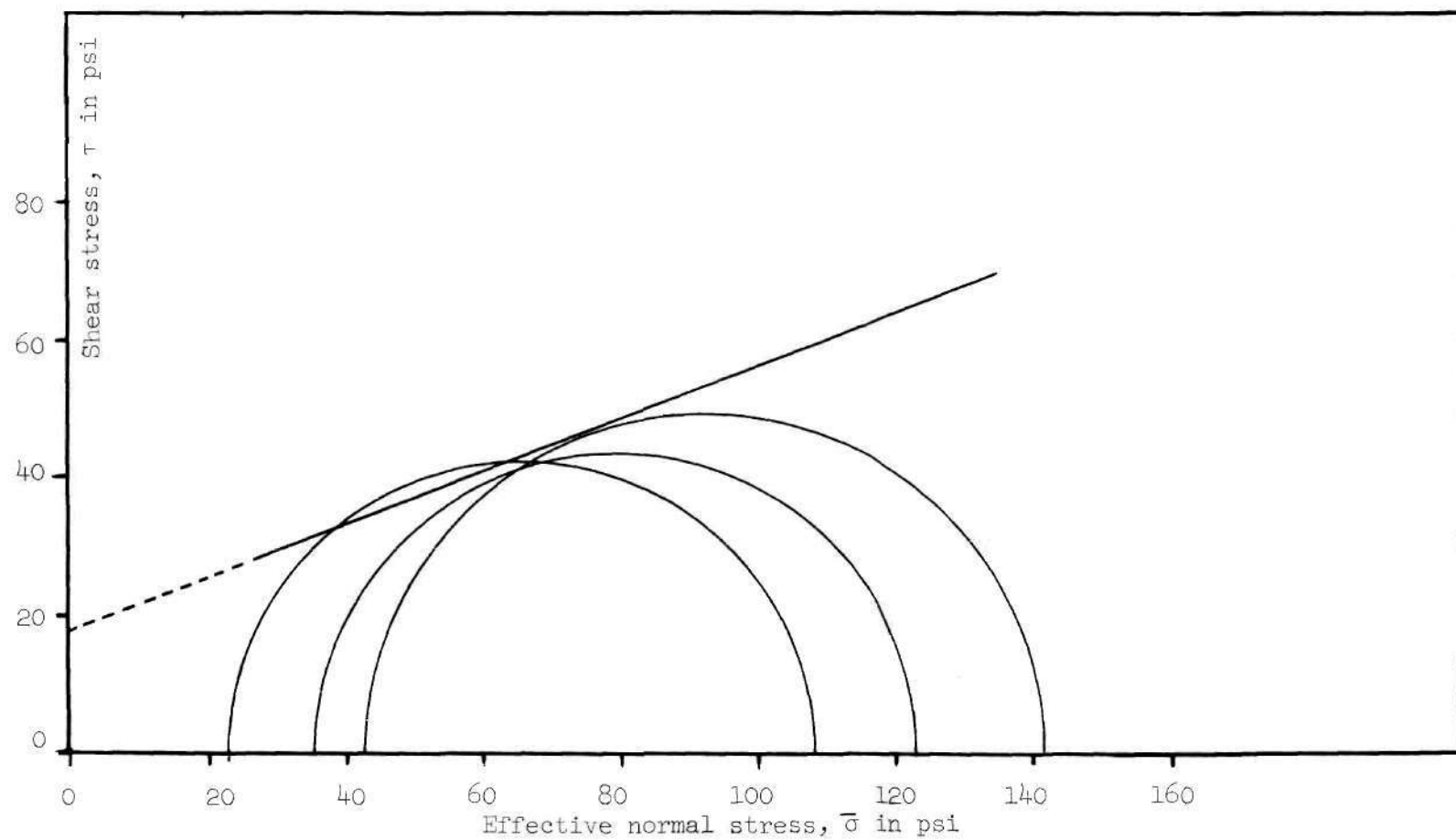


Figure 38. Mohr Circles
 Admixture: Tergitol TP-9
 Percent Admixture: 0.5

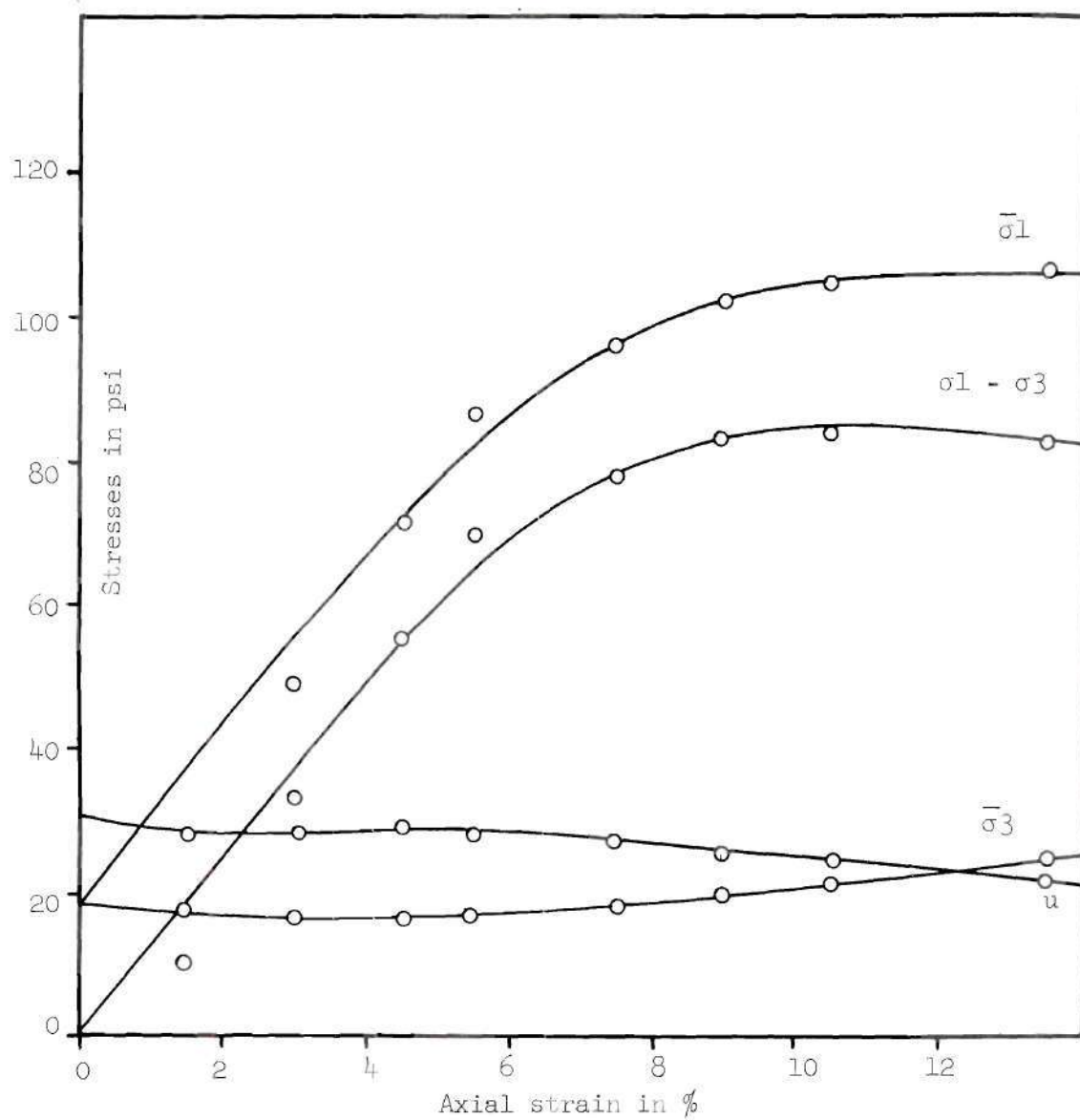


Figure 39. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 0.75
 All around Pressure: 45 psi

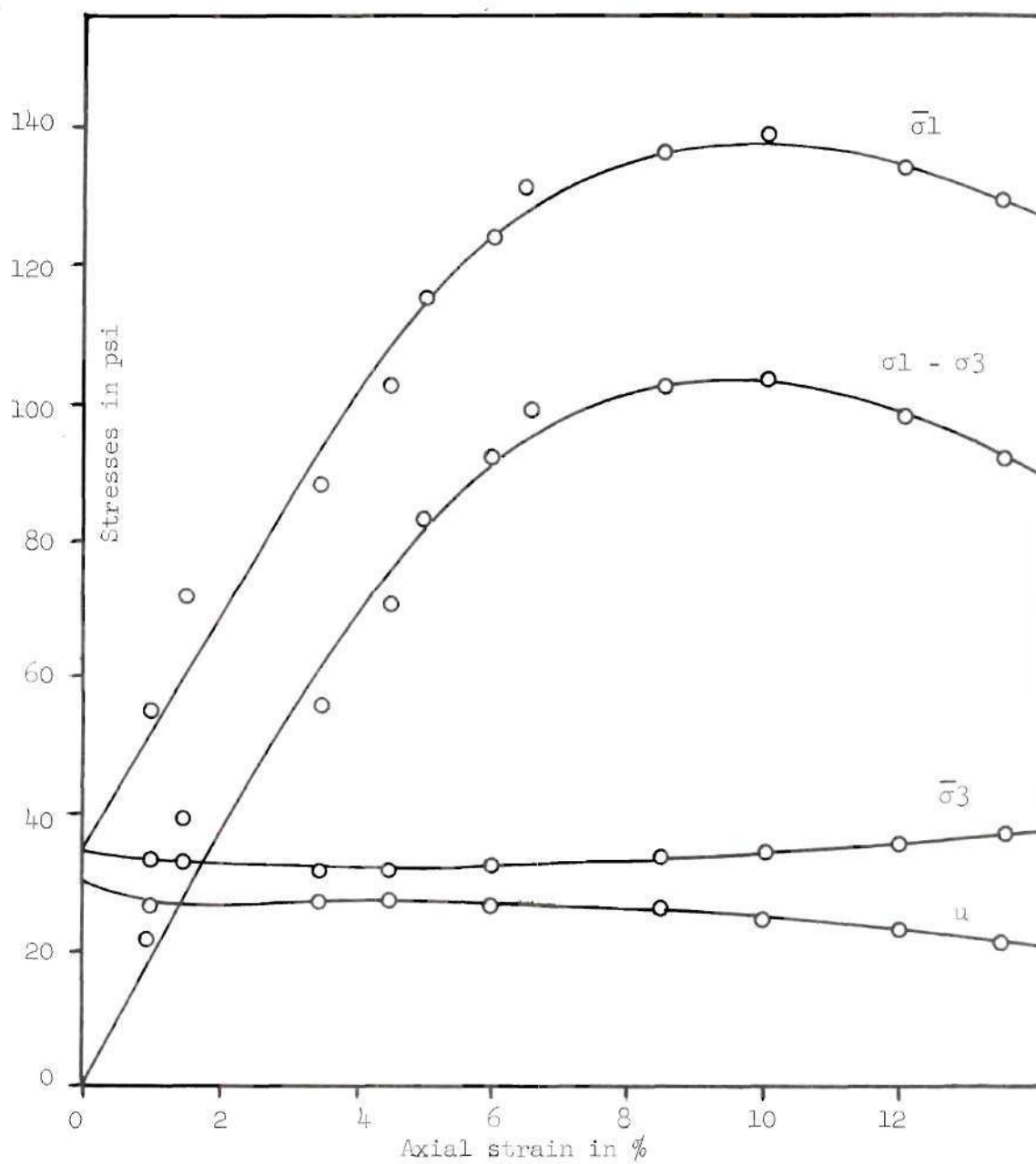


Figure 40. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 0.75
 All around Pressure: 60 psi

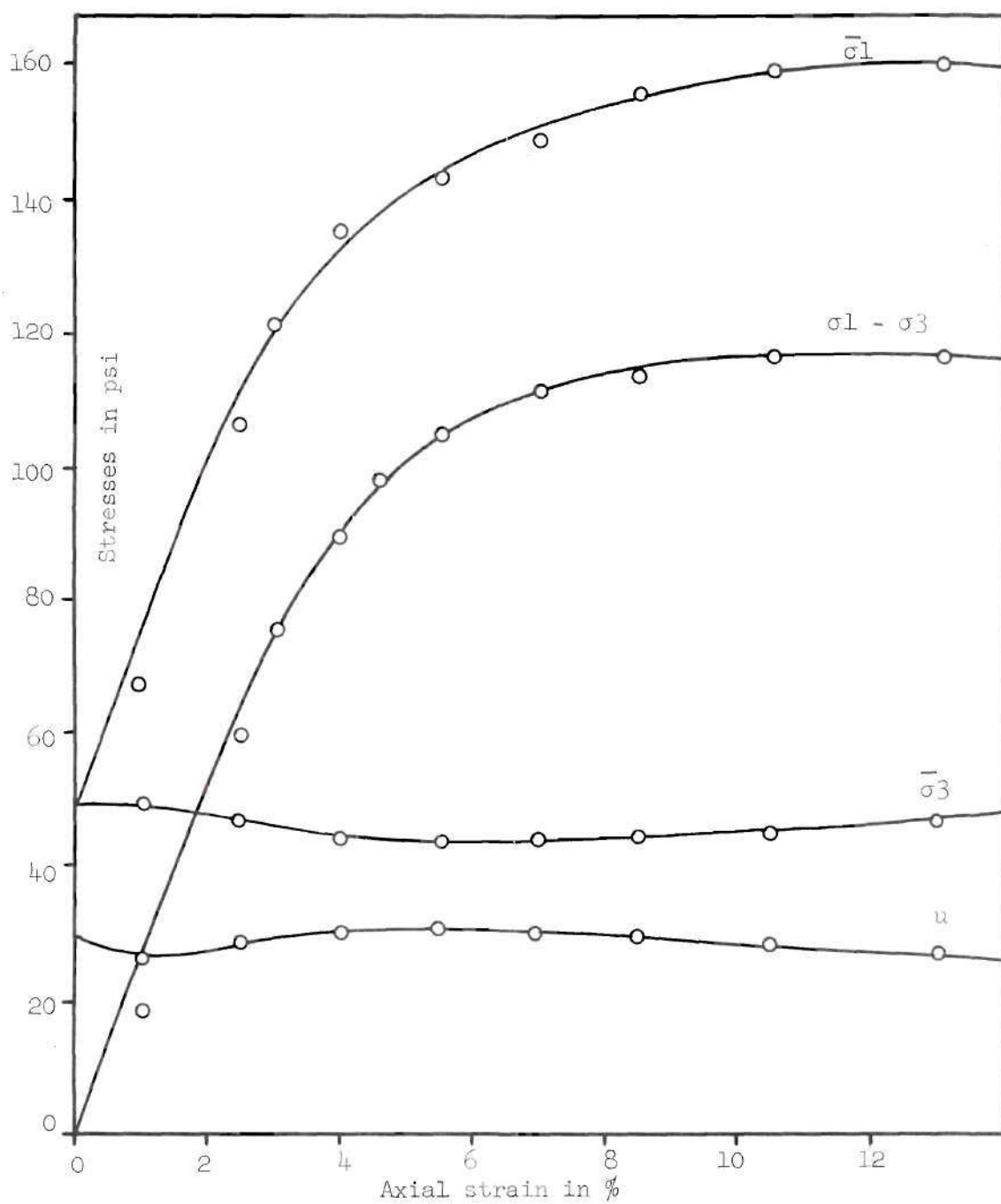


Figure 41. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 0.75
 All around Pressure: 75 psi

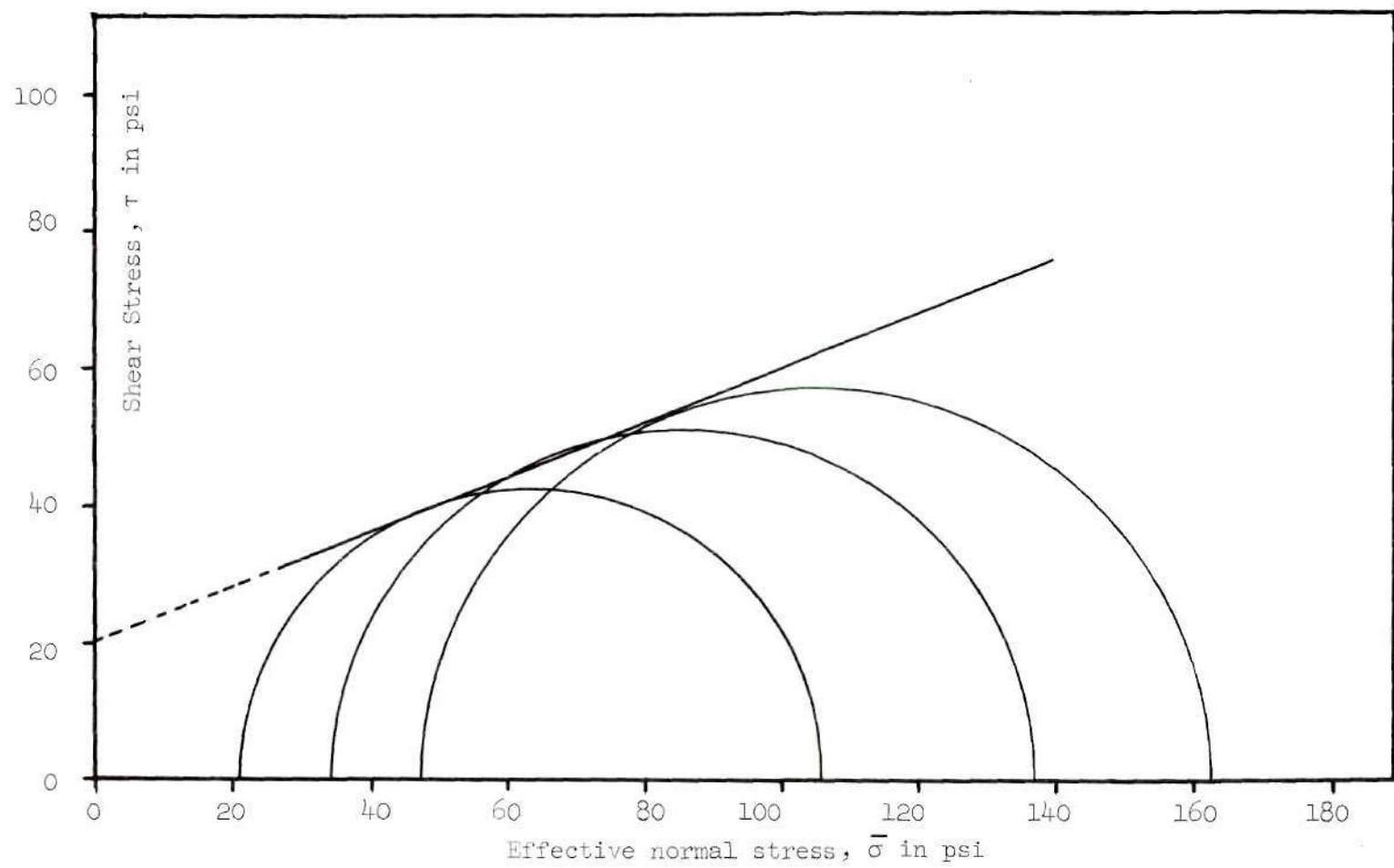


Figure 42. Mohr Circles
 Admixture: Tergitol TP-9
 Percent Admixture: 0.75

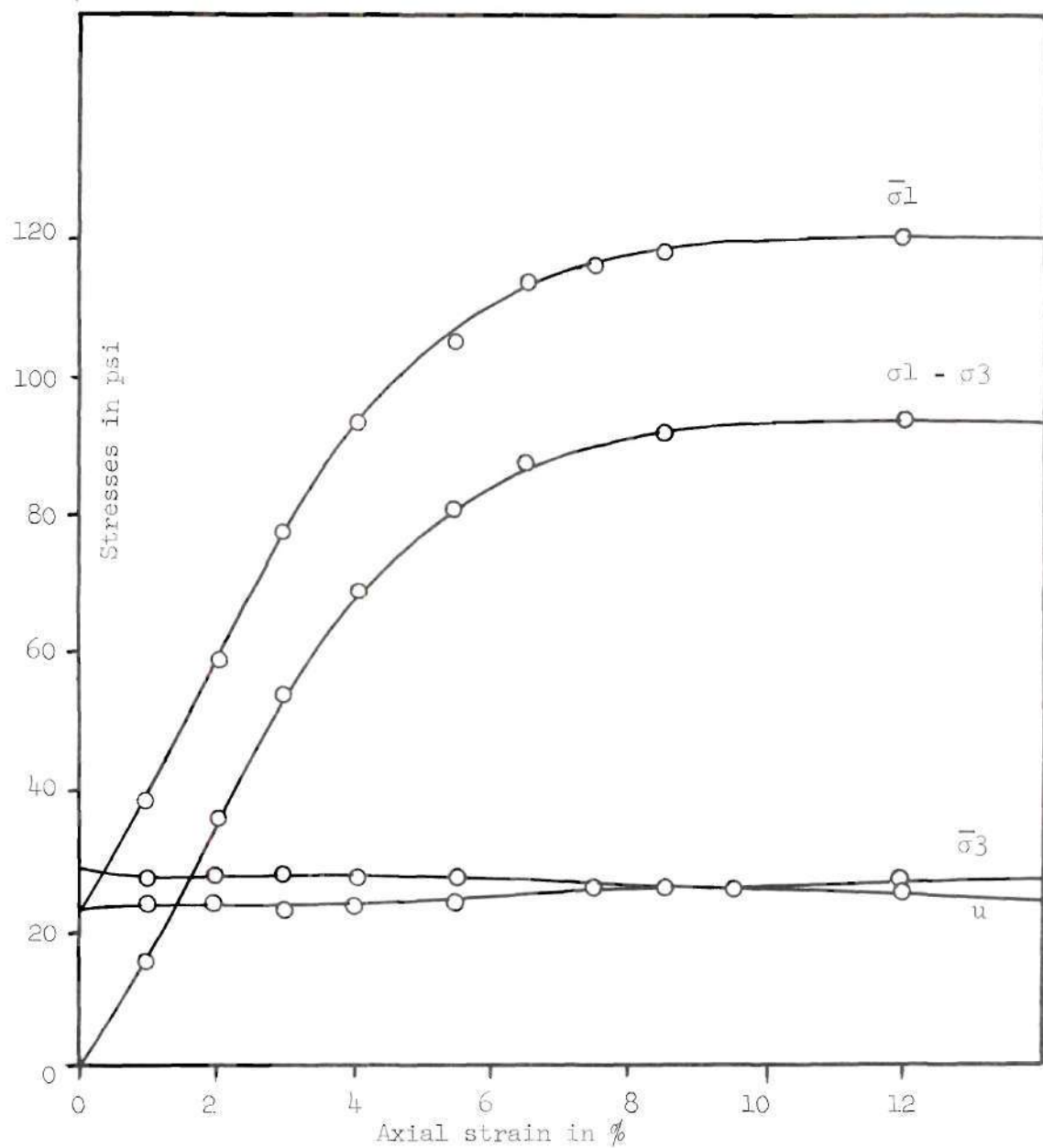


Figure 43. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 1.0
 All around Pressure: 45 psi

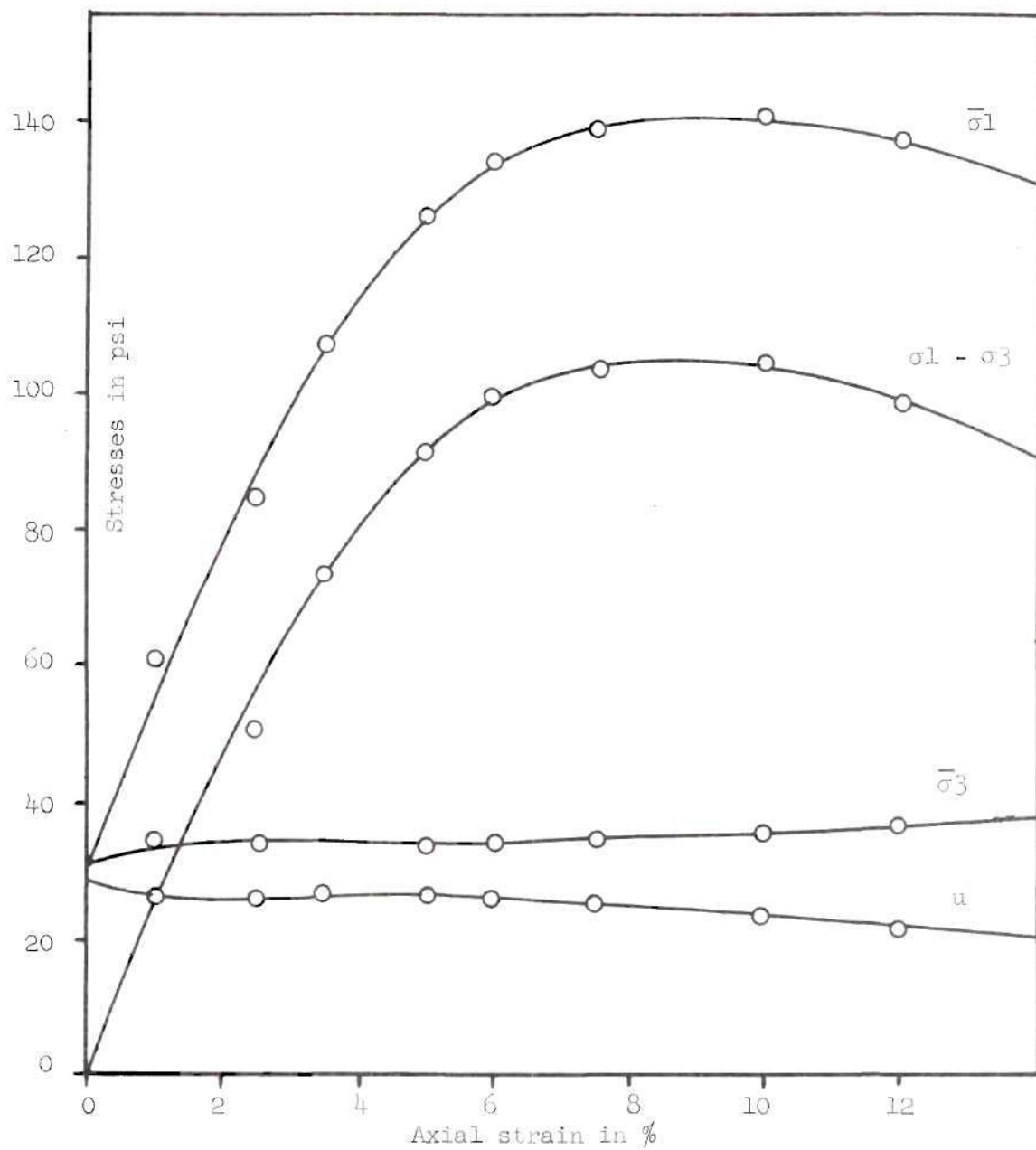


Figure 44. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 1.0
 All around Pressure: 60 psi

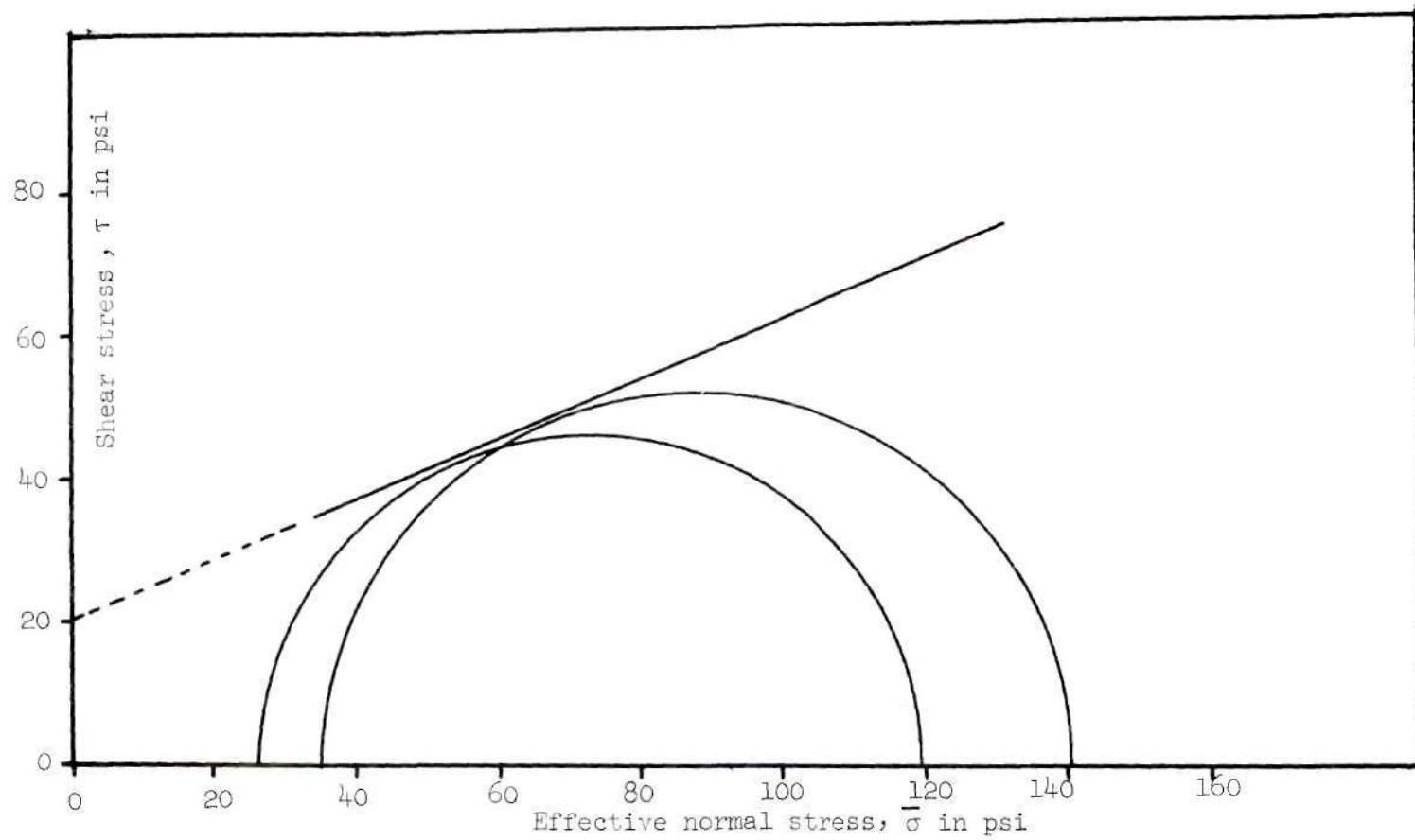


Figure 45. Mohr Circles
Admixture: Tergitol TP-9
Percent Admixture: 1.0

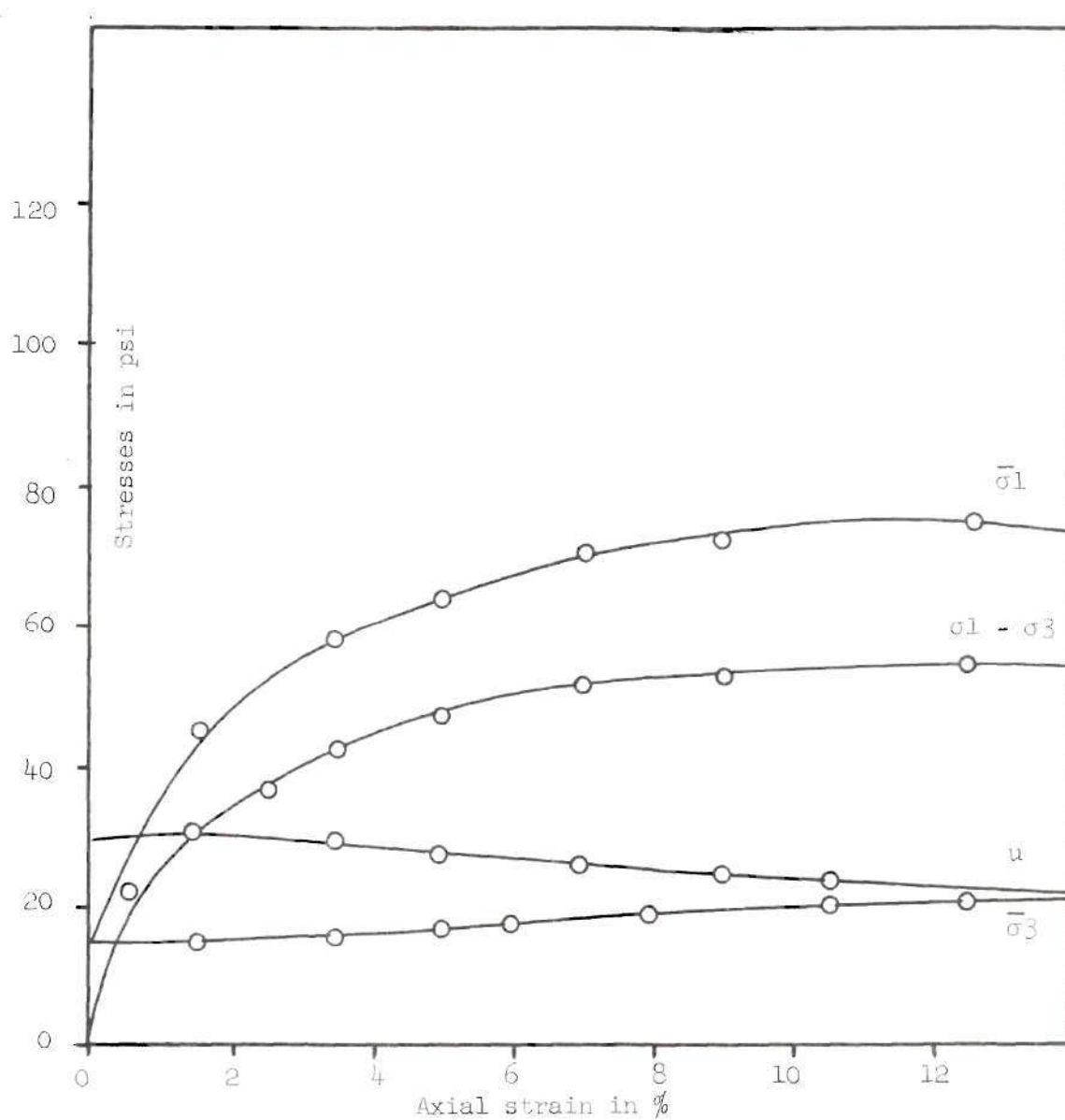


Figure 46. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 1.5
 All around Pressure: 45 psi

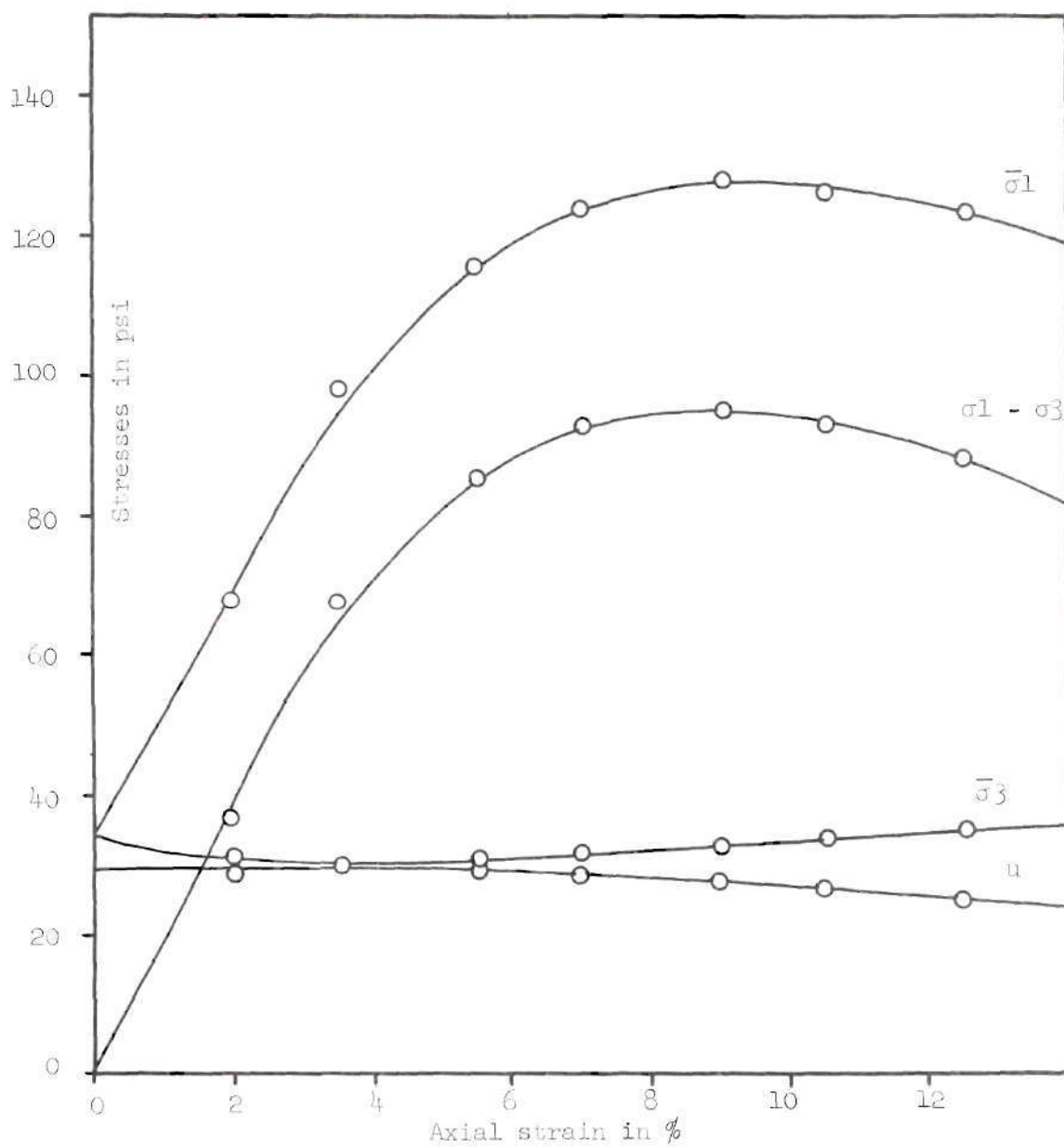


Figure 47. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 1.5
 All around Pressure: 60 psi

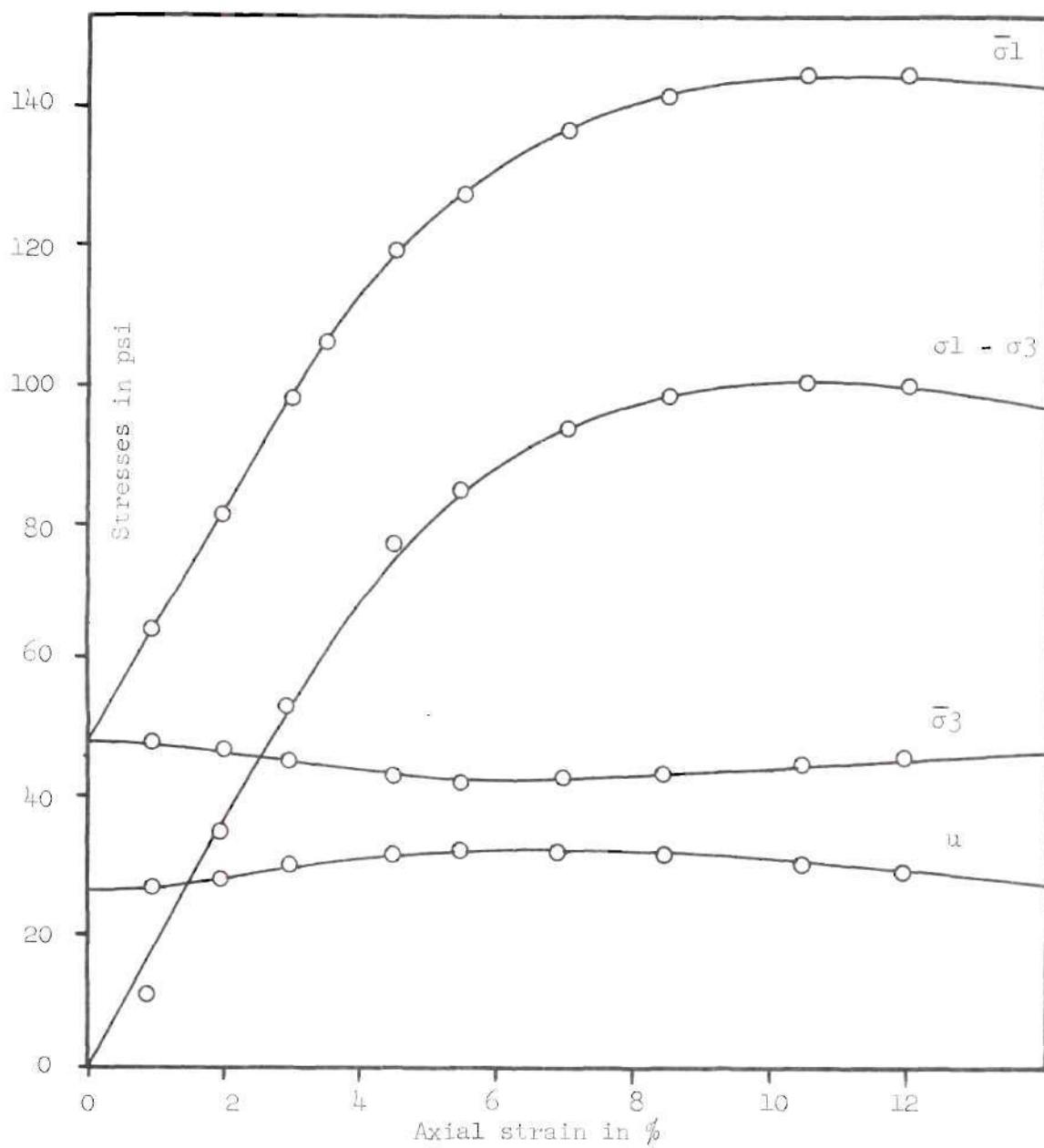


Figure 48. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 1.5
 All around Pressure: 75 psi

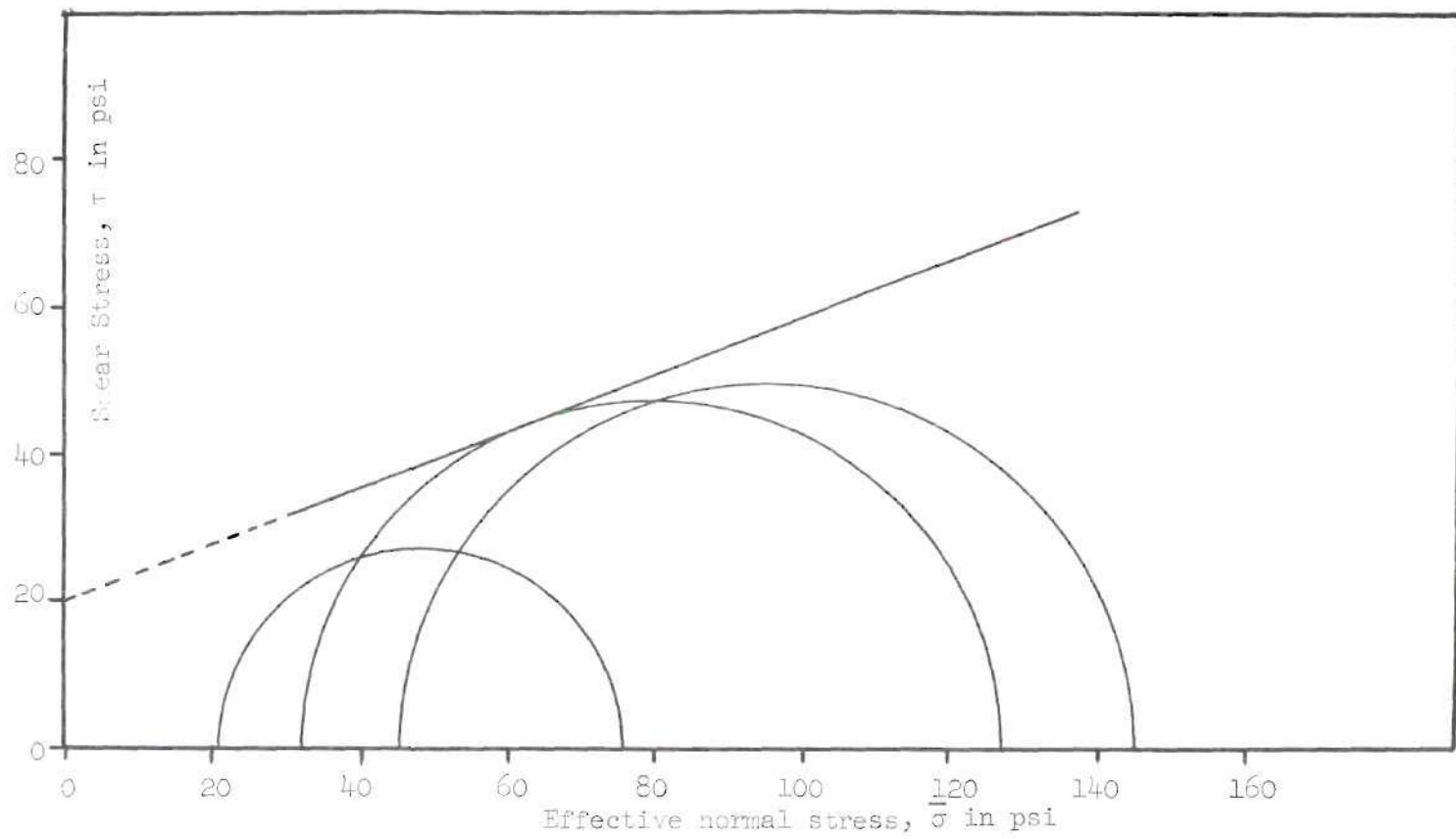


Figure 49. Mohr Circles
 Admixture: Tergitol IP-9
 Percent Admixture: 1.5

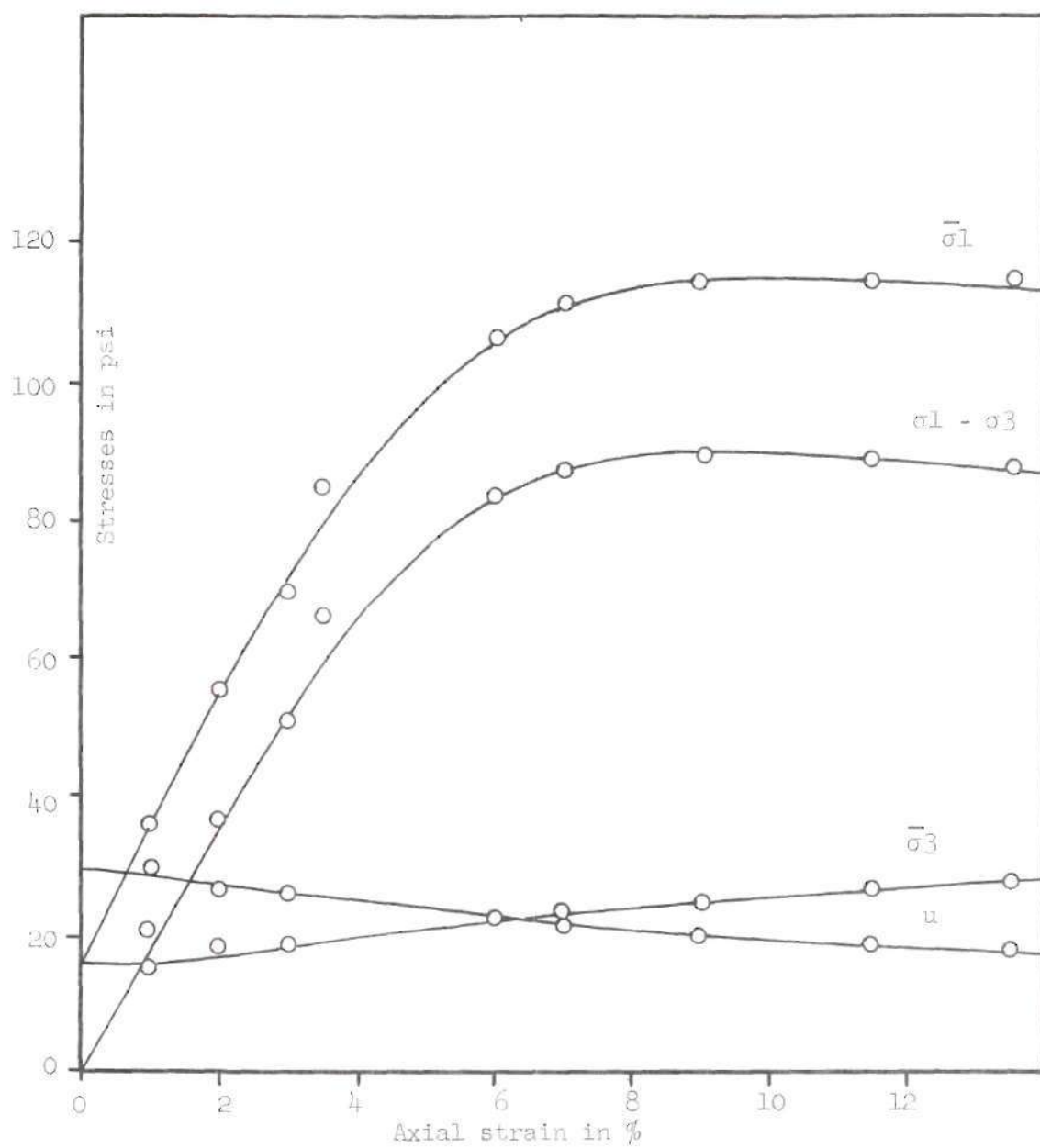


Figure 50. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 2.0
 All around Pressure: 45 psi

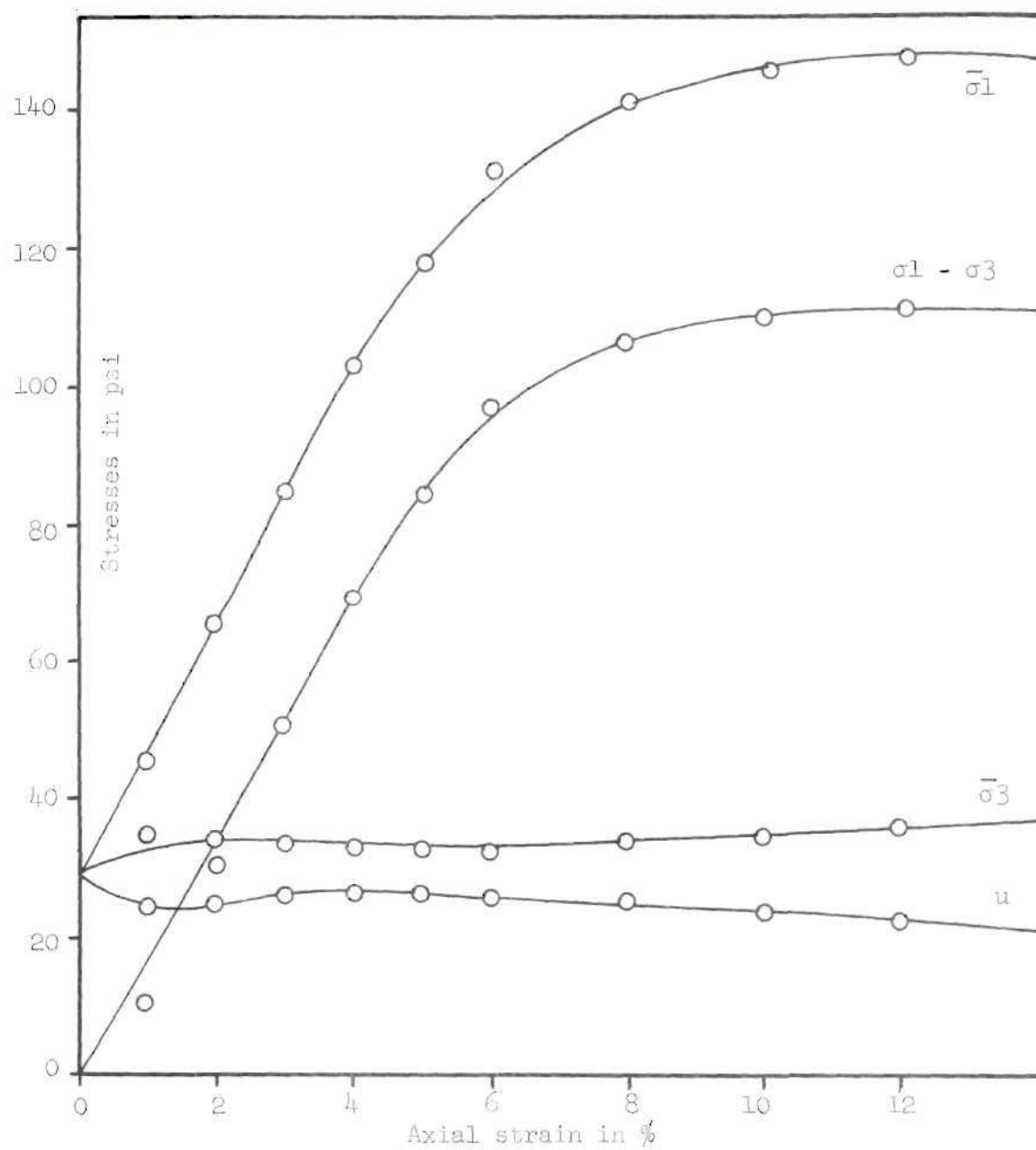


Figure 51. Triaxial Compression Test
 Admixture: Tergitol TP-9
 Percent Admixture: 2.0
 All around Pressure: 60 psi

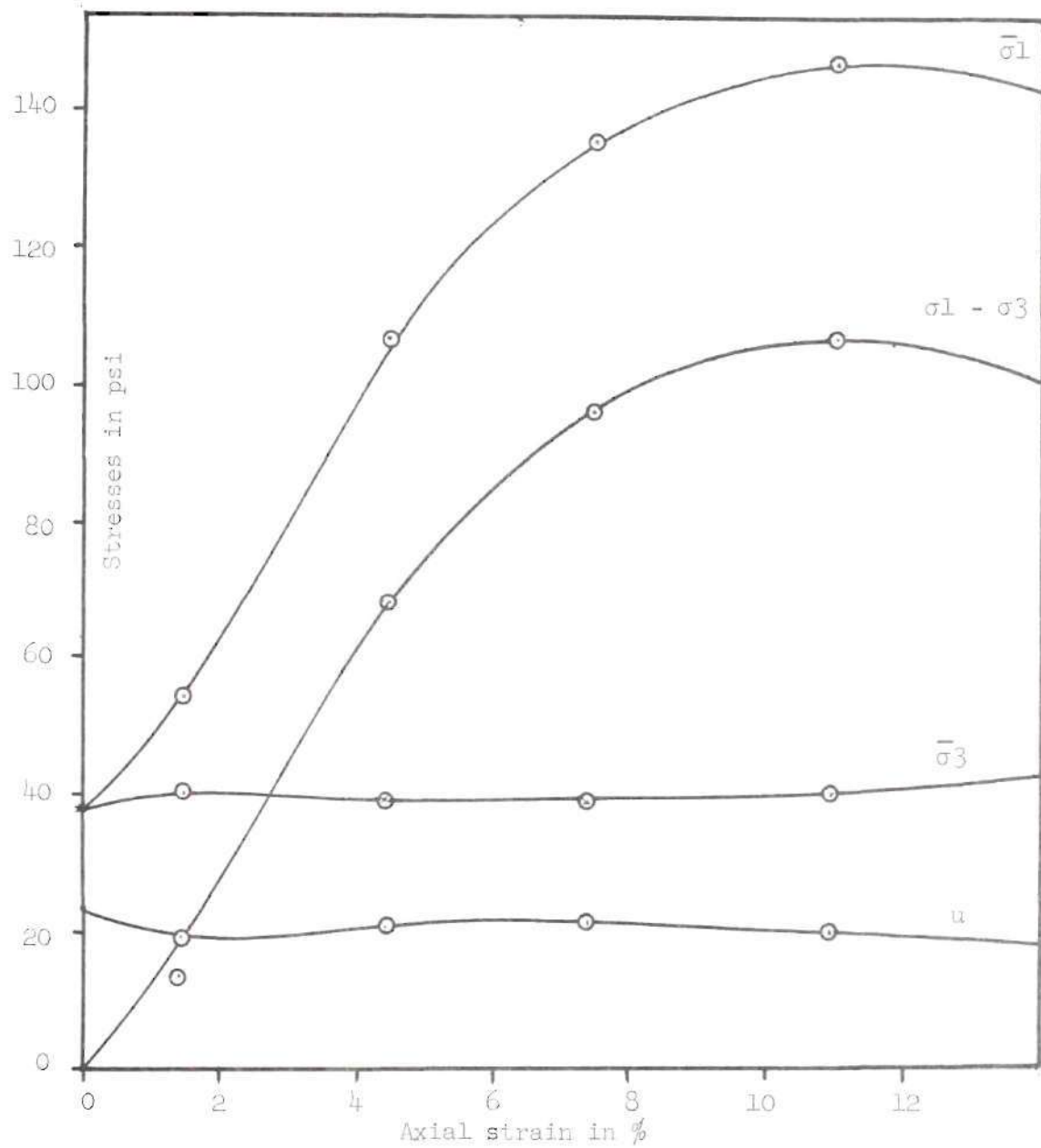


Figure 52. Triaxial Compression Test.
 Admixture: Tergitol TP-9
 Percent Admixture: 2.0
 All around Pressure: 75 psi

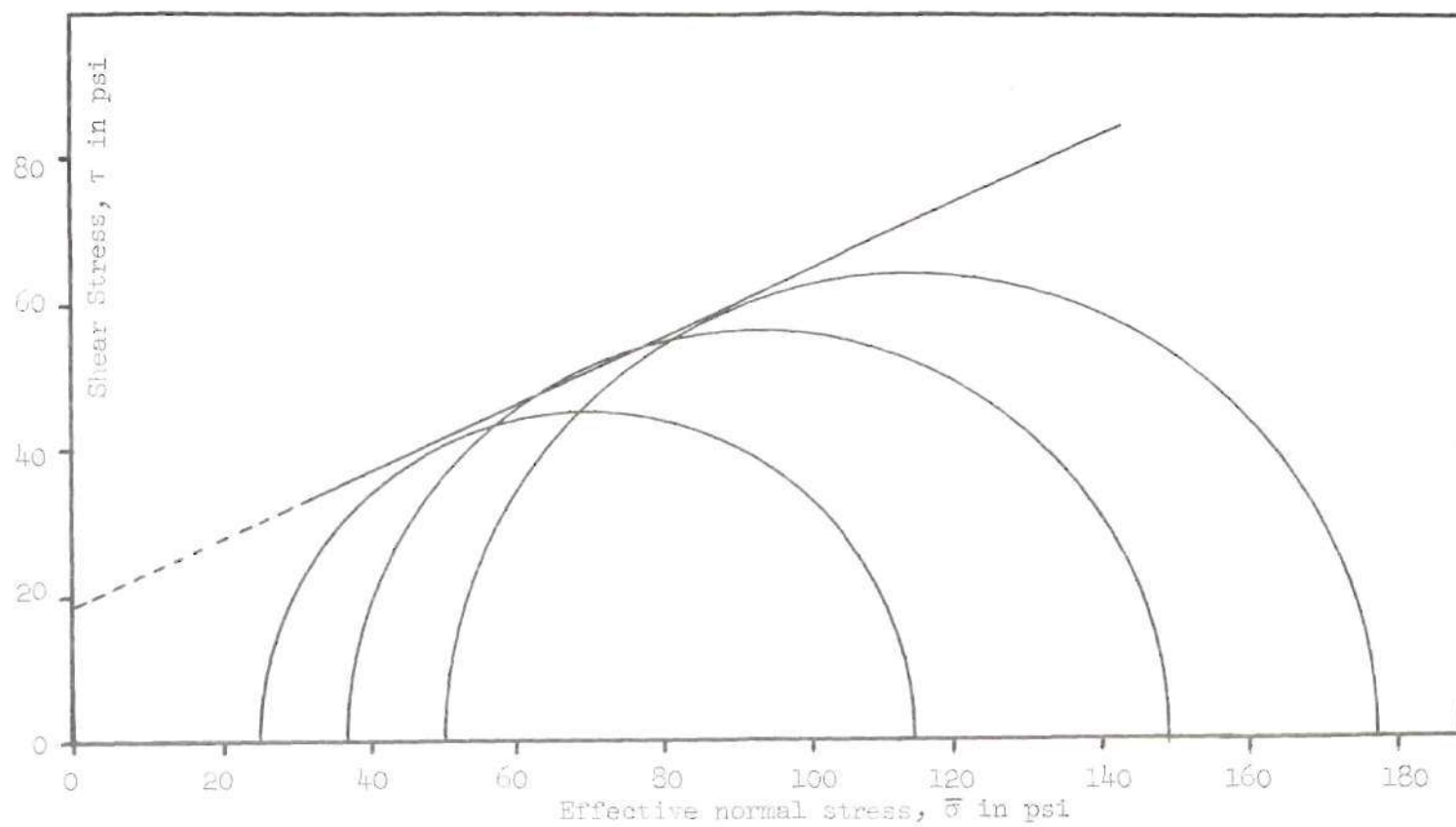


Figure 53. Mohr Circles
 Admixture: Tergitol TP-9
 Percent Admixture: 2.0

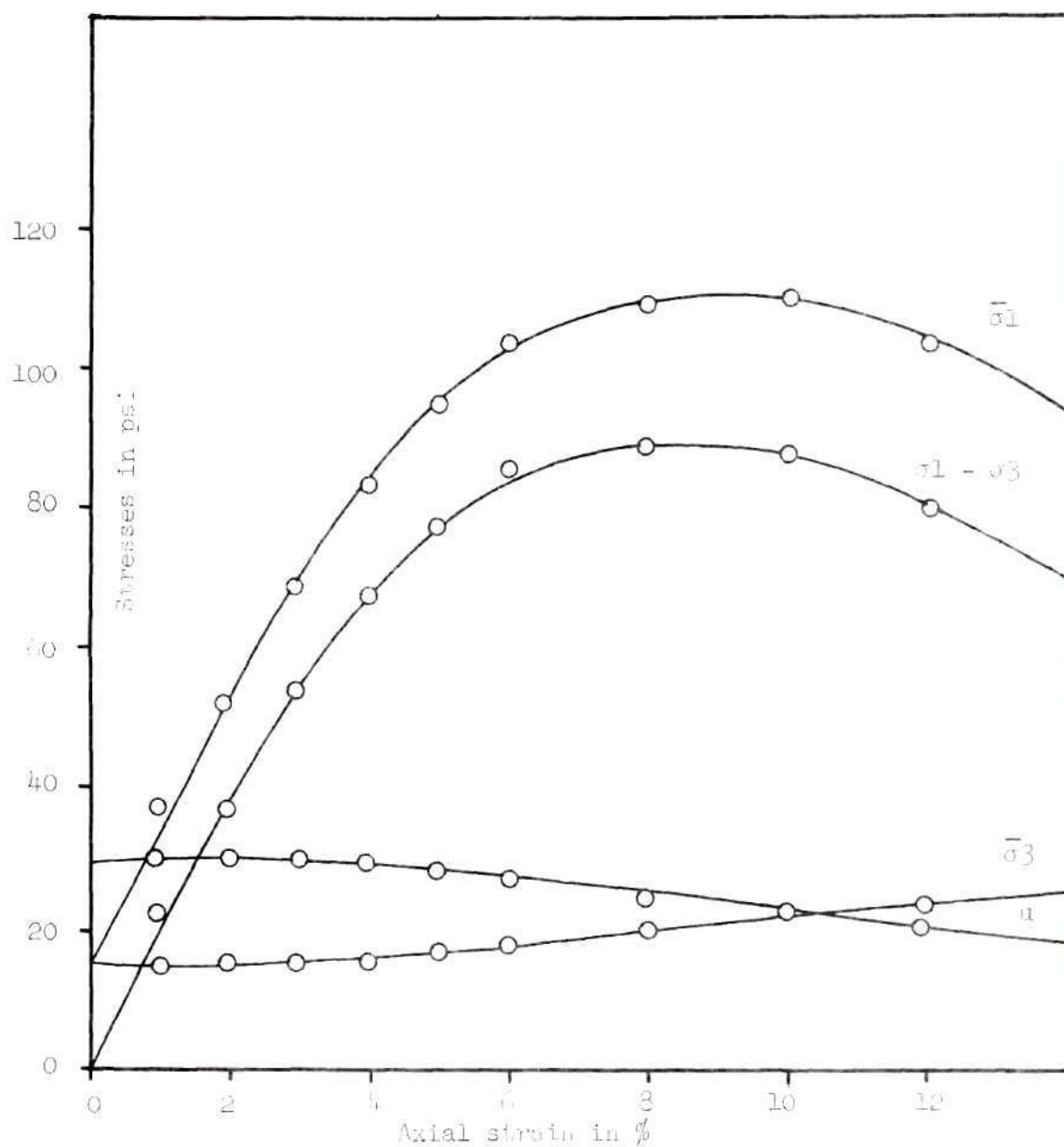


Figure 94. Triaxial Compression Test
 Admixture: Tergitol FP-9
 Percent Admixture: 3.0
 All around Pressure: 45 psi

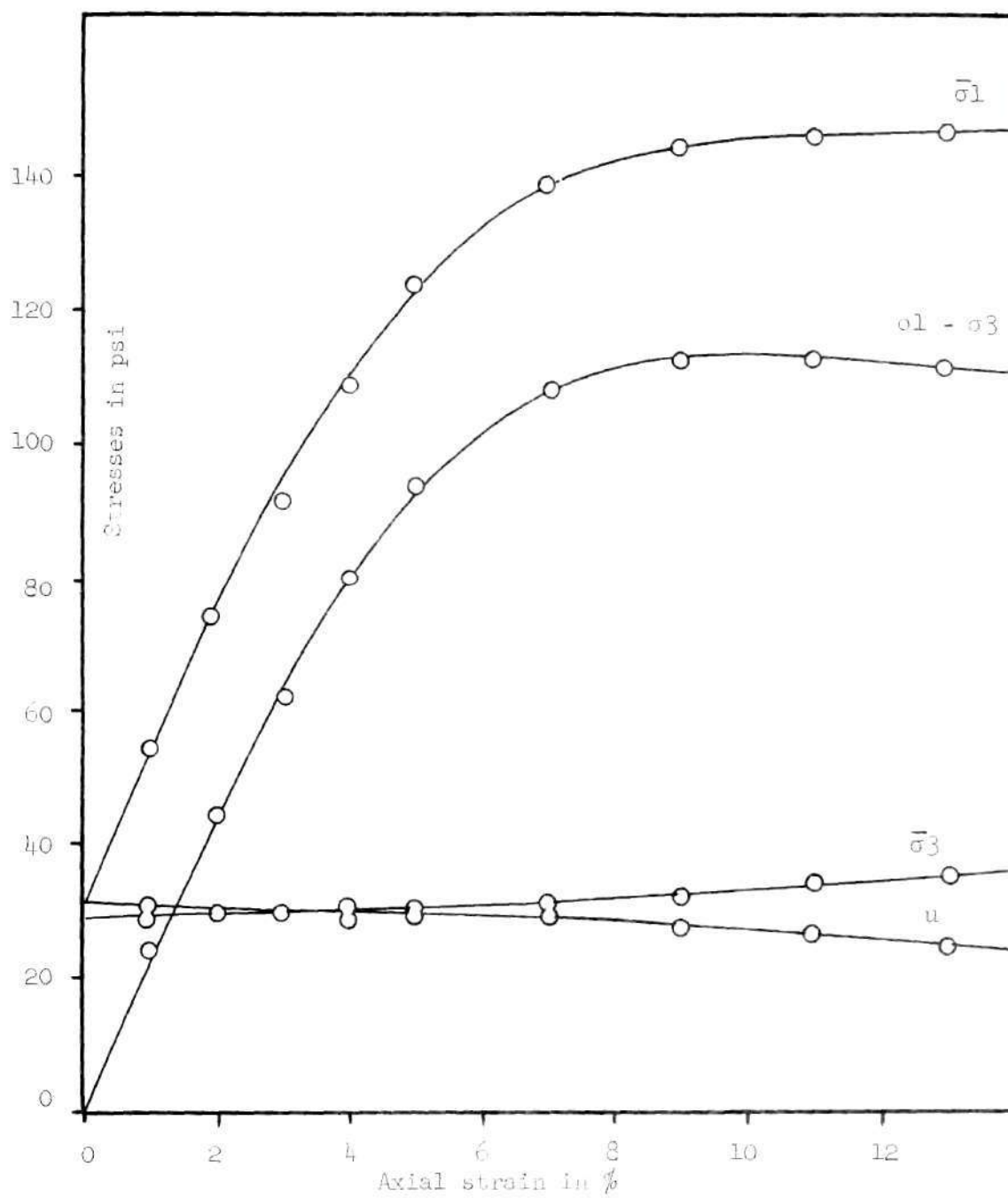


Figure 35. Triaxial Compression Test
 Admixture: Tergitol IP-9
 Percent Admixture: 3.0
 All around Pressure: 60 psi

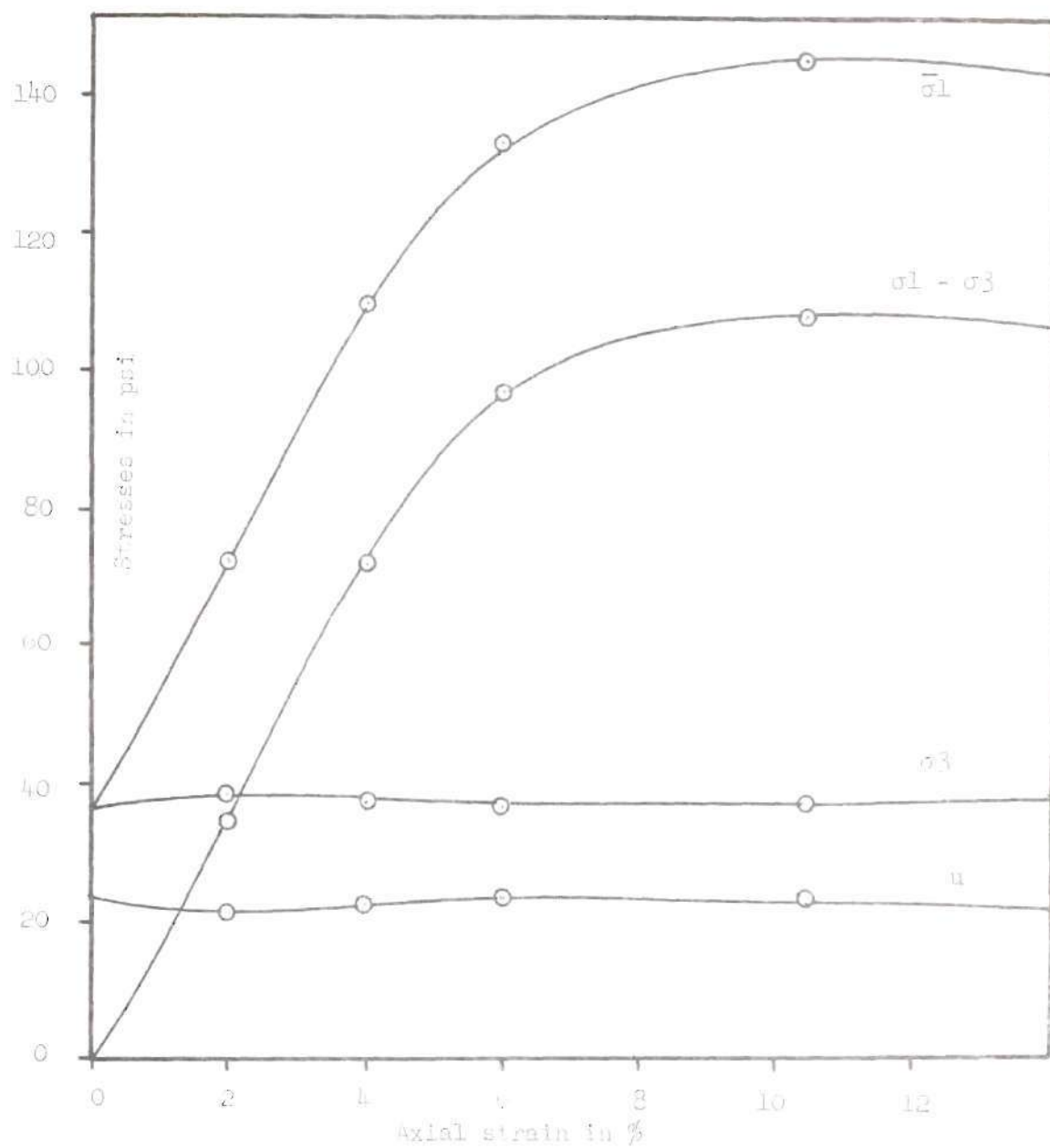


Figure 5a. Triaxial Compression Test:
 Admixture: Tergitol TF-9
 Percent Admixture: 3.0
 All around Pressure: 75 psi

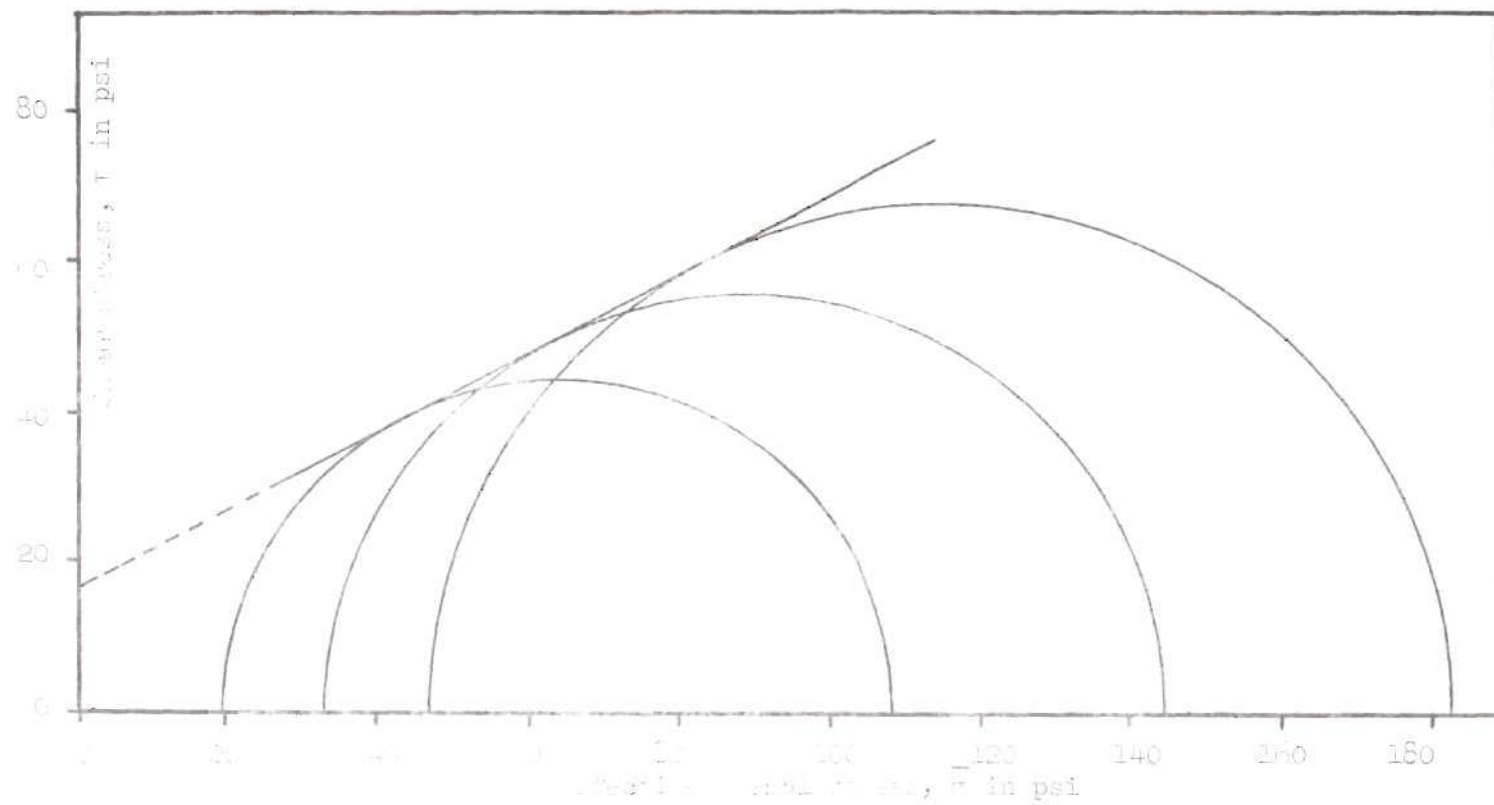


Figure 51: Failure Envelopes
 Units: σ in psi, τ in psi
 Factor: Factor = 3.0

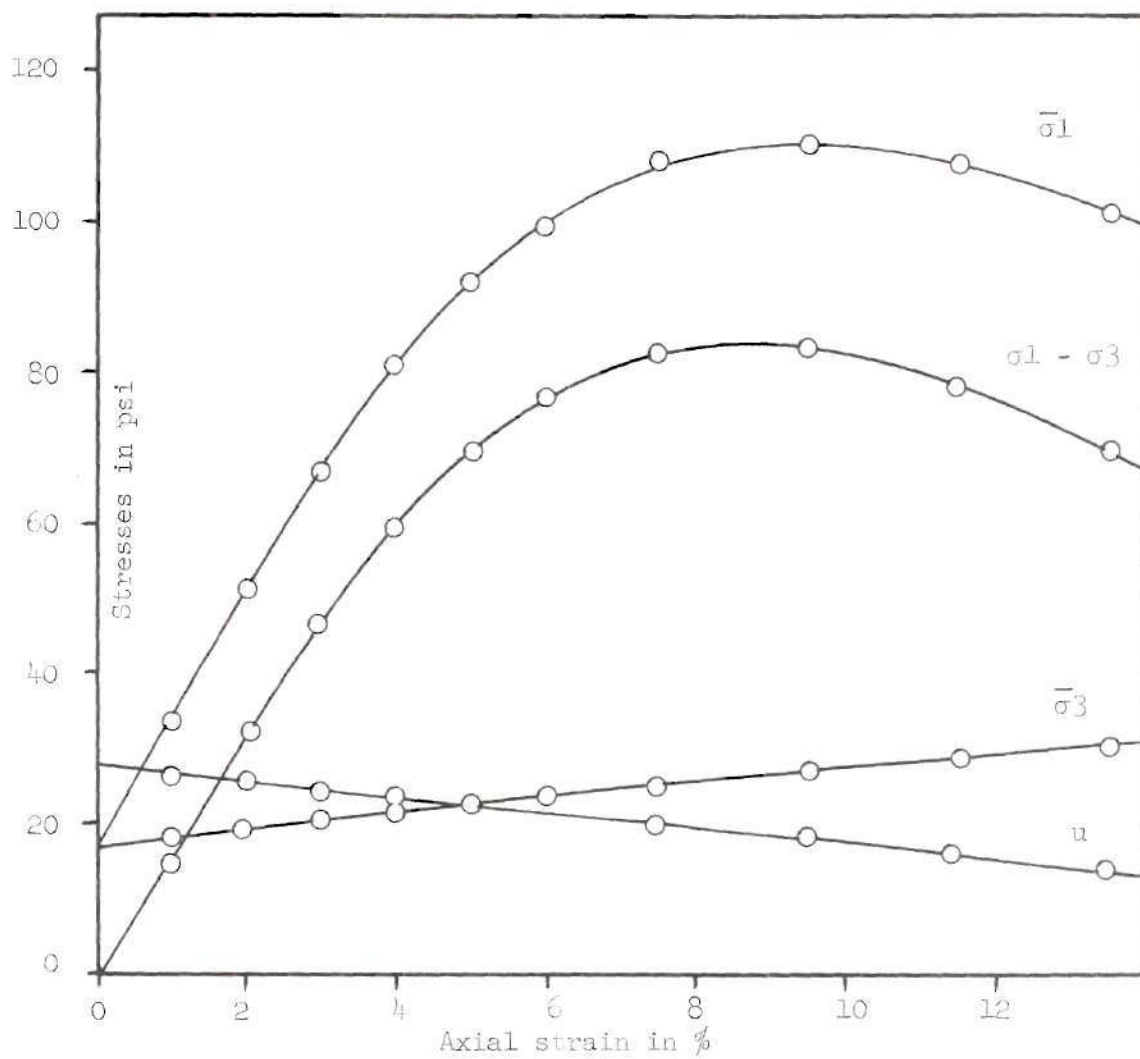


Figure 58. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 0.25
 All around Pressure: 45 psi

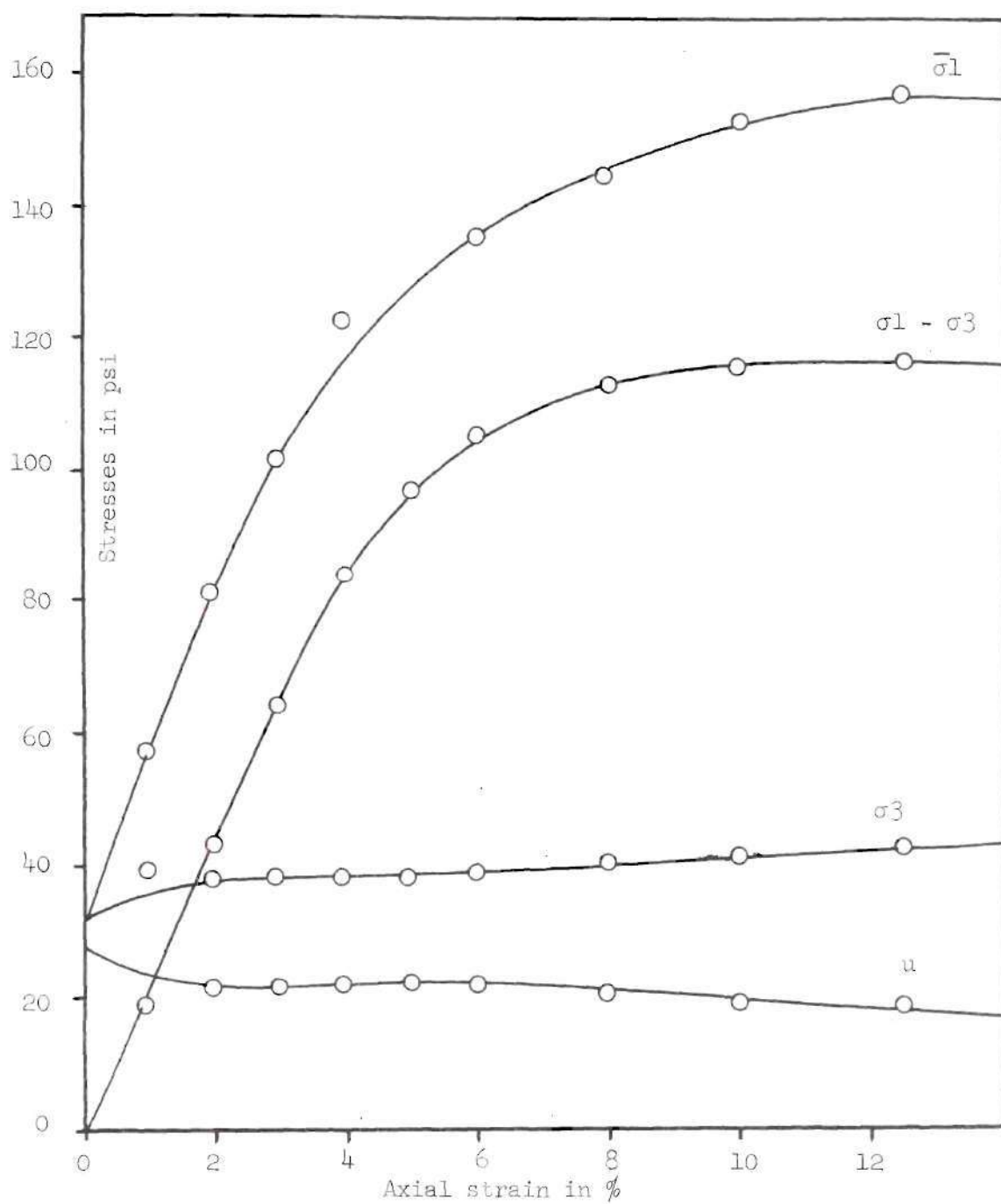


Figure 59. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 0.25
 All around Pressure: 60 psi

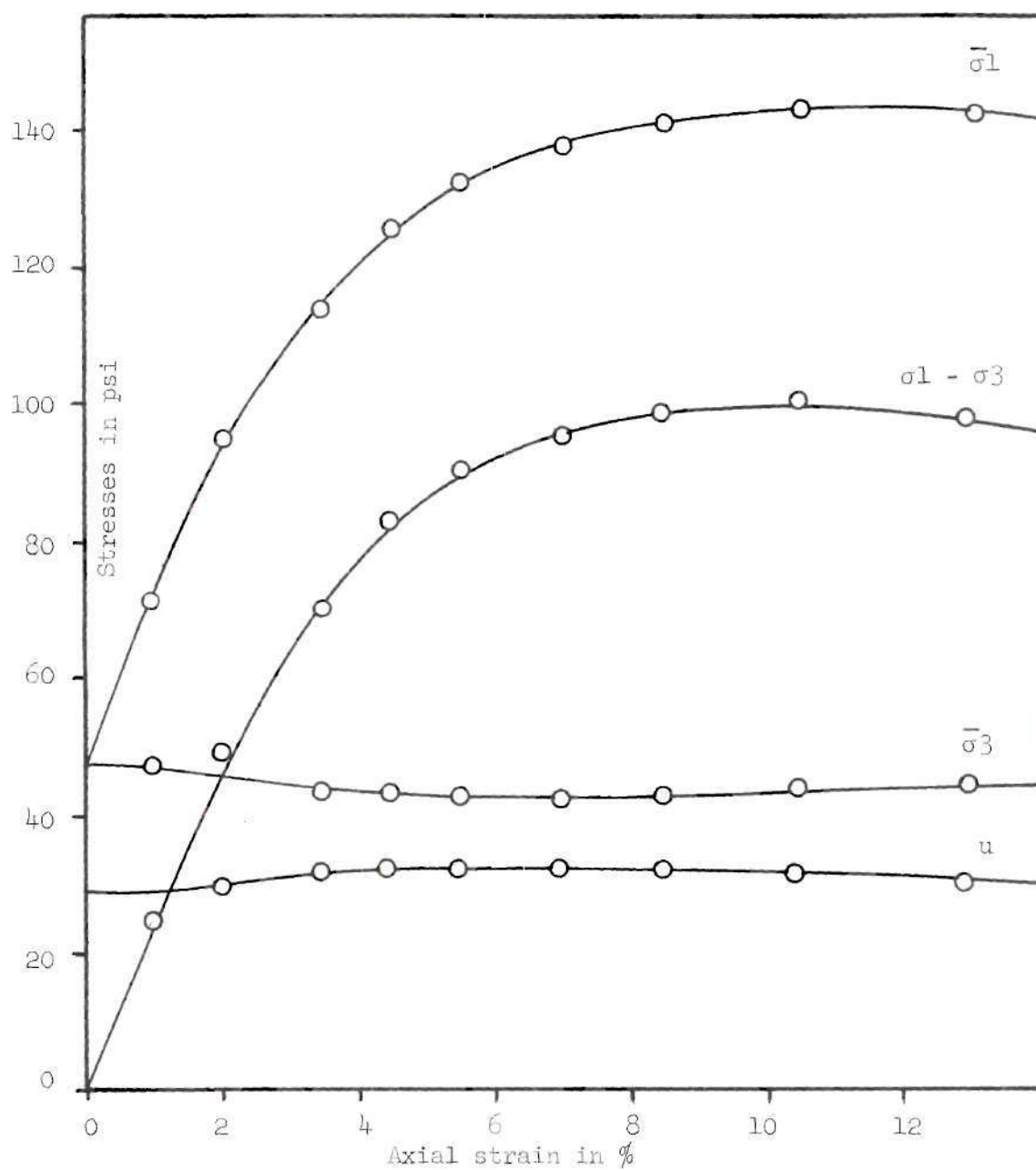


Figure 60. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 0.25
 All around Pressure: 75 psi

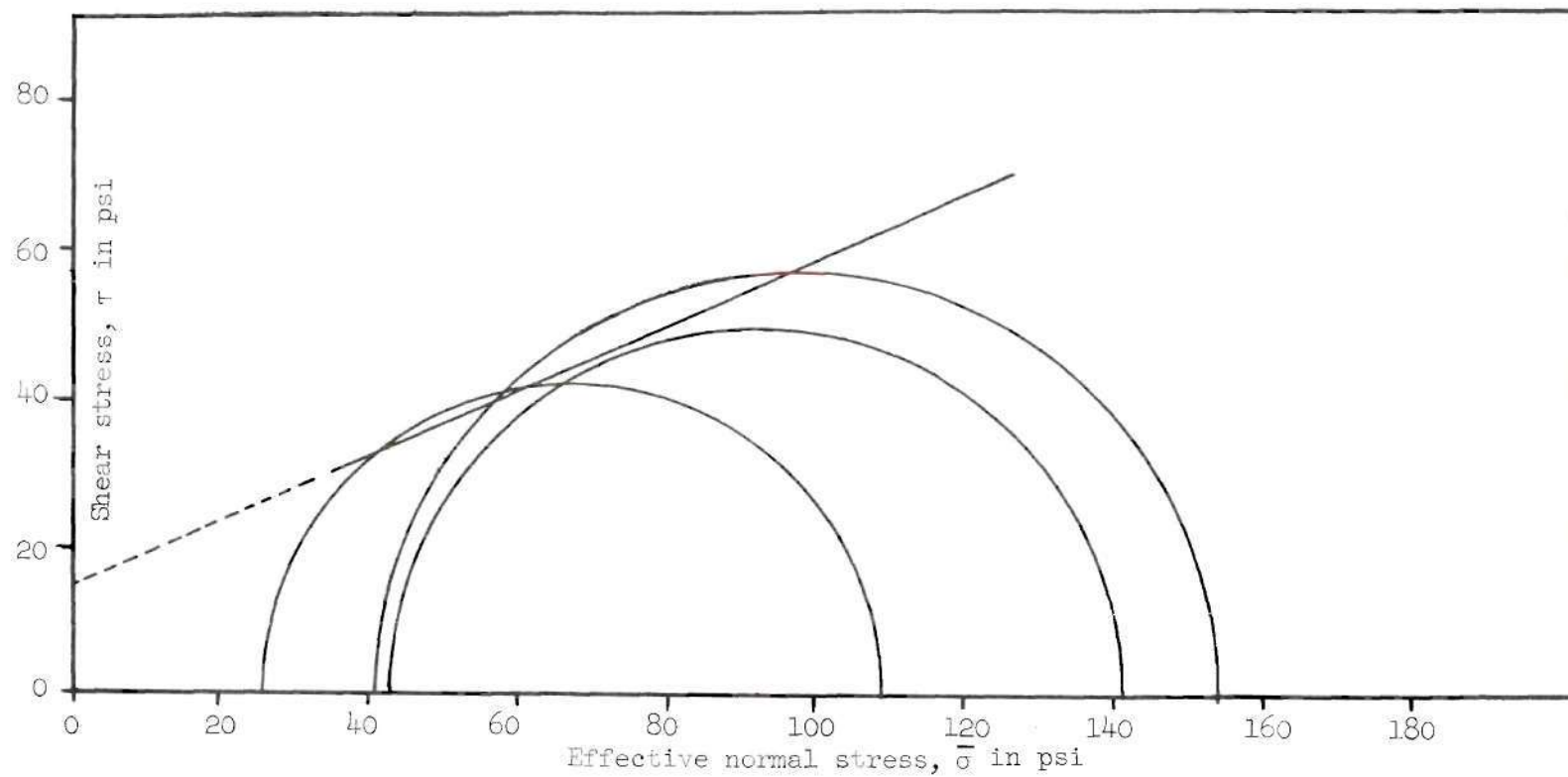


Figure 61. Mohr Circles
 Admixture: Polytergent LF-405
 Percent Admixture: 0.25

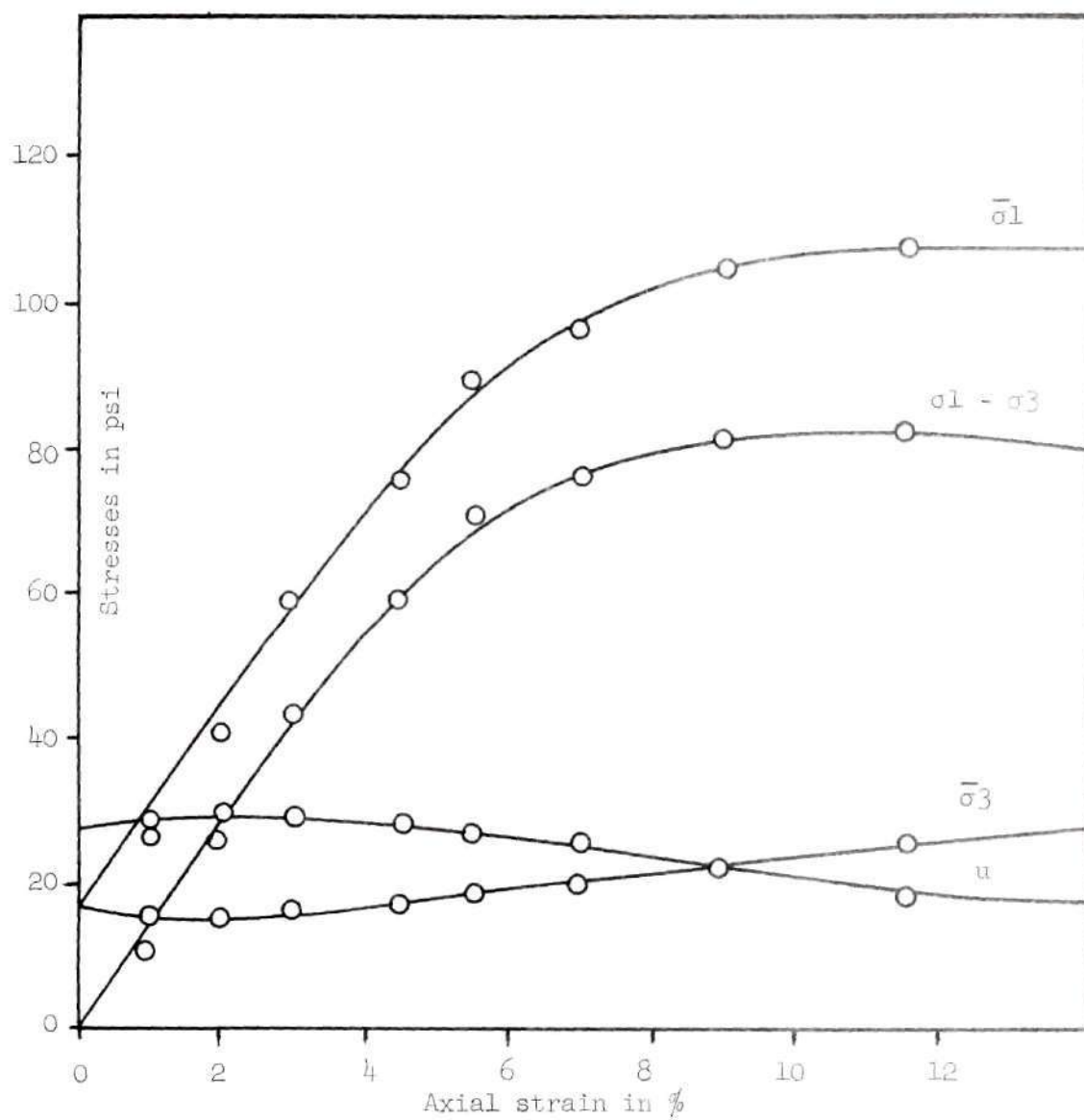


Figure 62. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 0.5
 All around Pressure: 45 psi

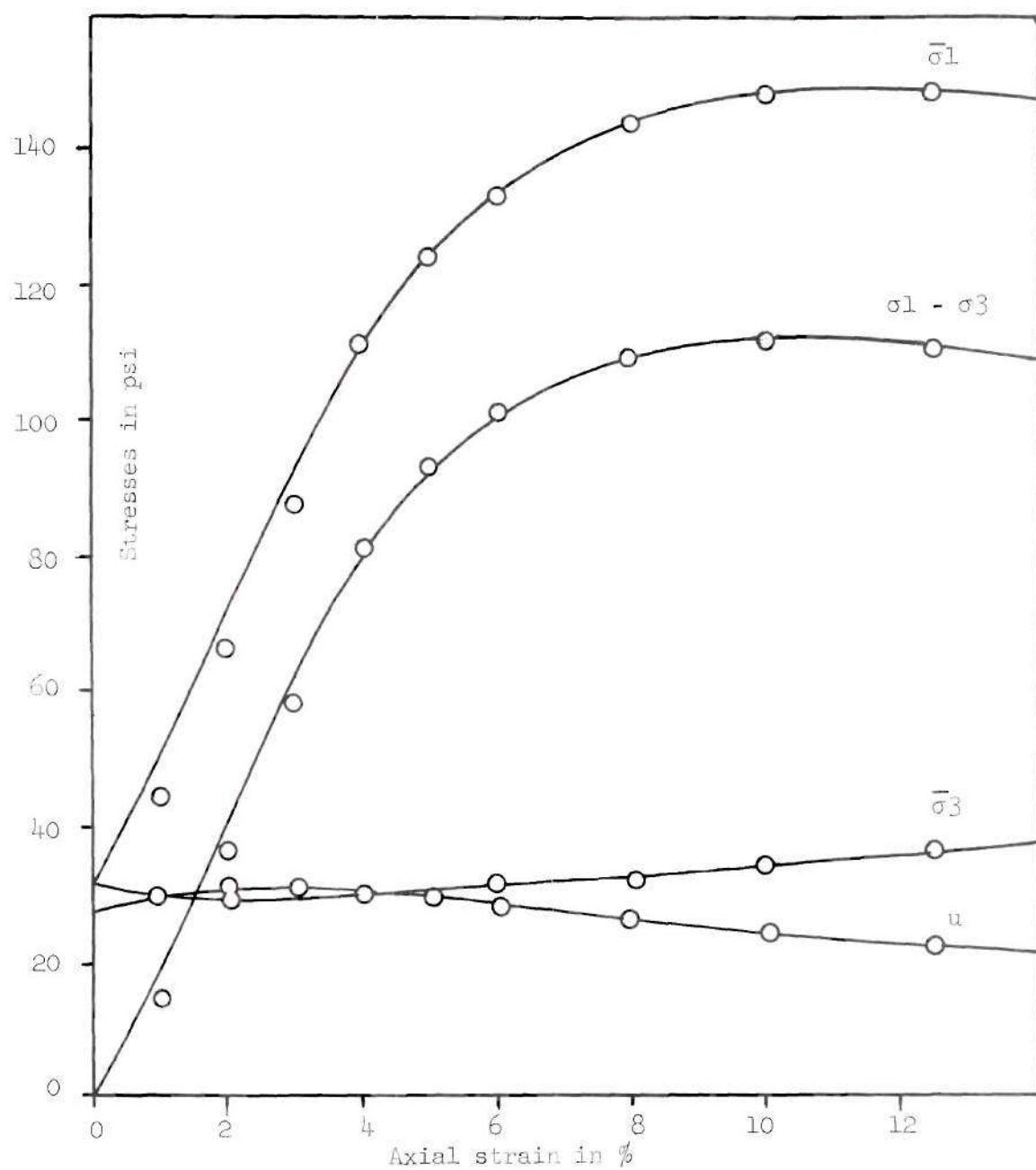


Figure 63. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 0.5
 All around Pressure: 60 psi

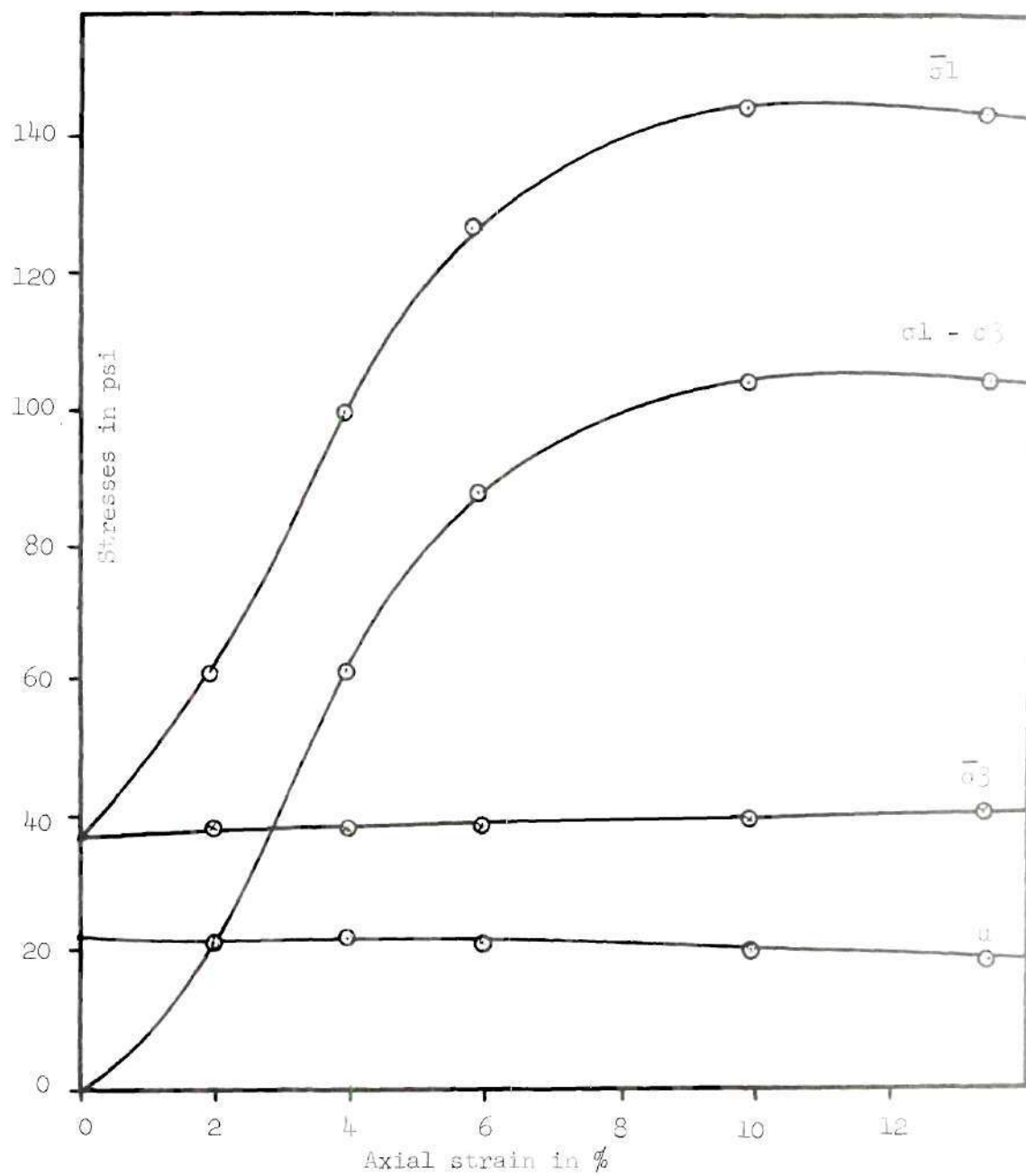


Figure 64. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 0.5
 All around Pressure: 75 psi

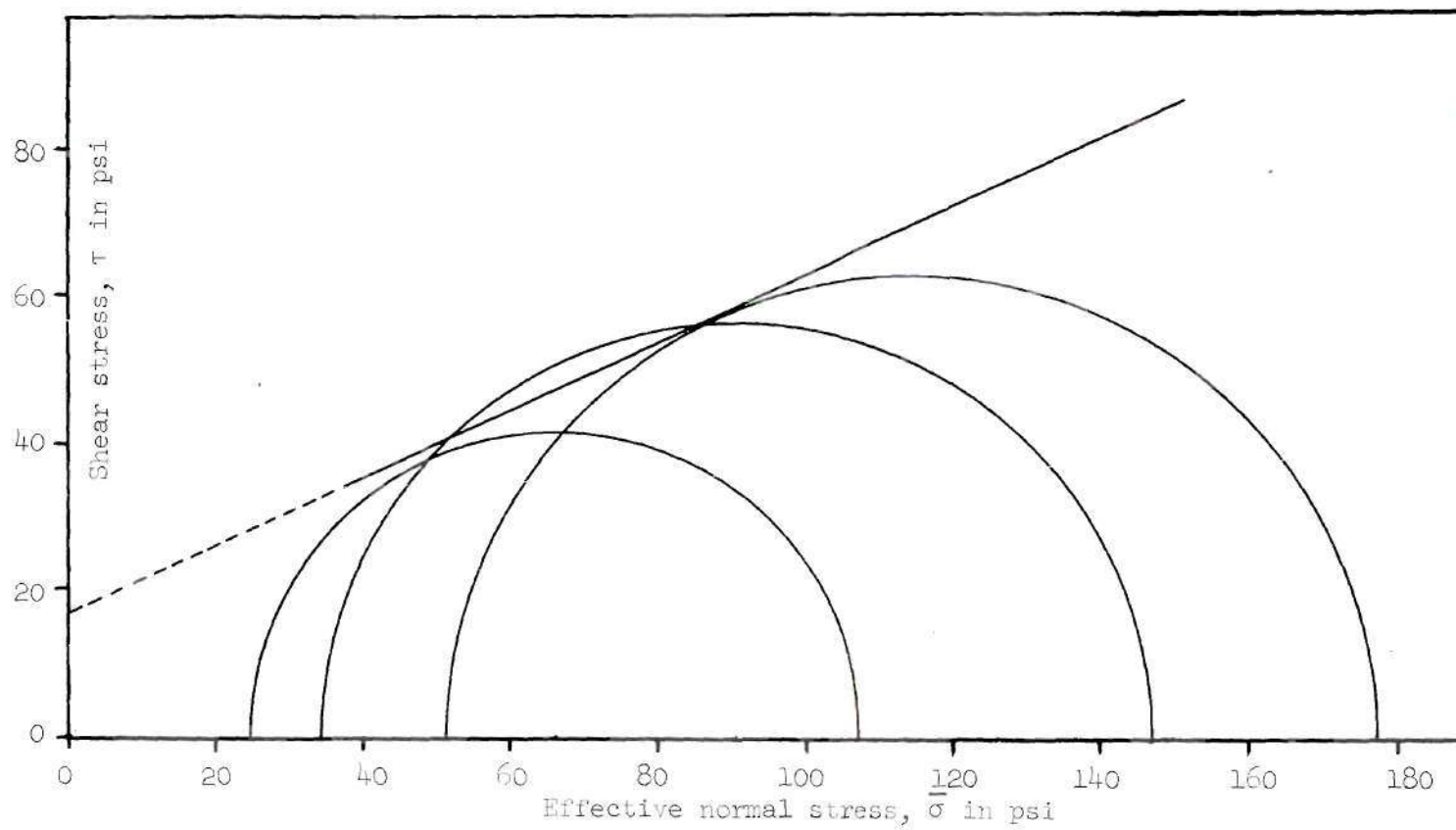


Figure 65. Mohr Circles
 Admixture: Polyttergent LF-405
 Percent Admixture: 0.5

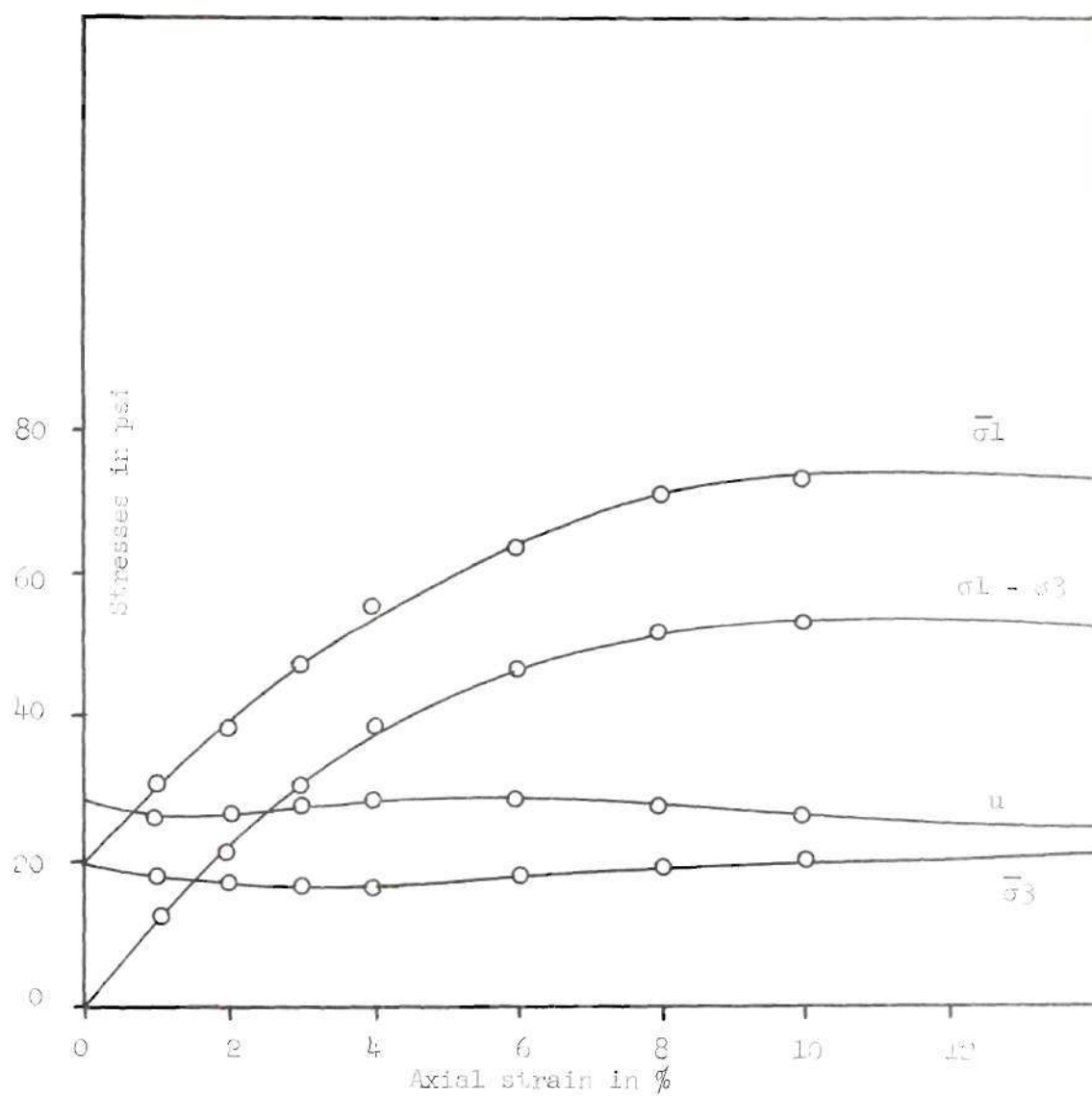


Figure 86. Triaxial Compression Test
 Admixture: Polytergent LF-405
 All around Pressure: 45 psi

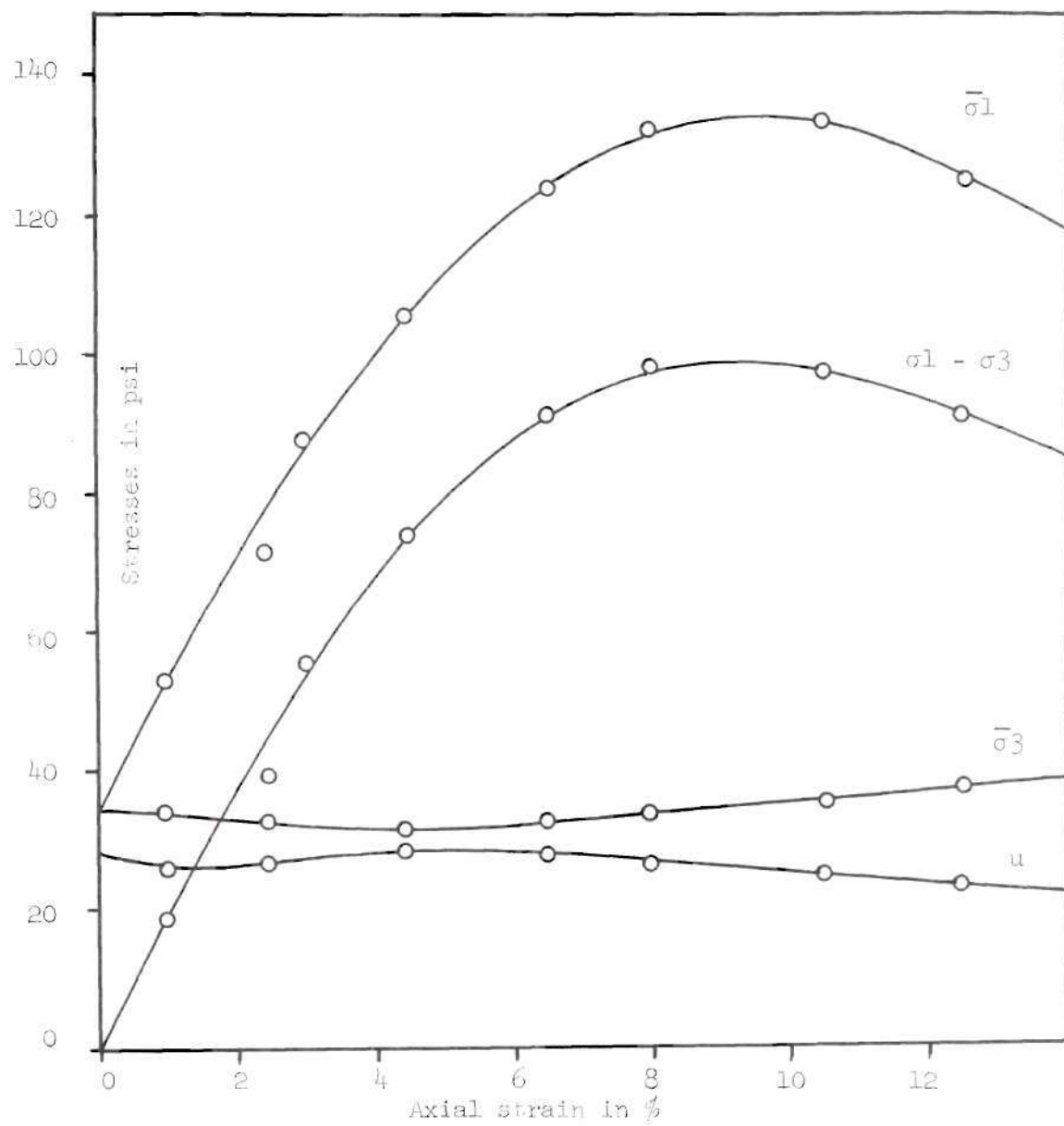


Figure 07. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 1.0
 All around Pressure: 60 psi

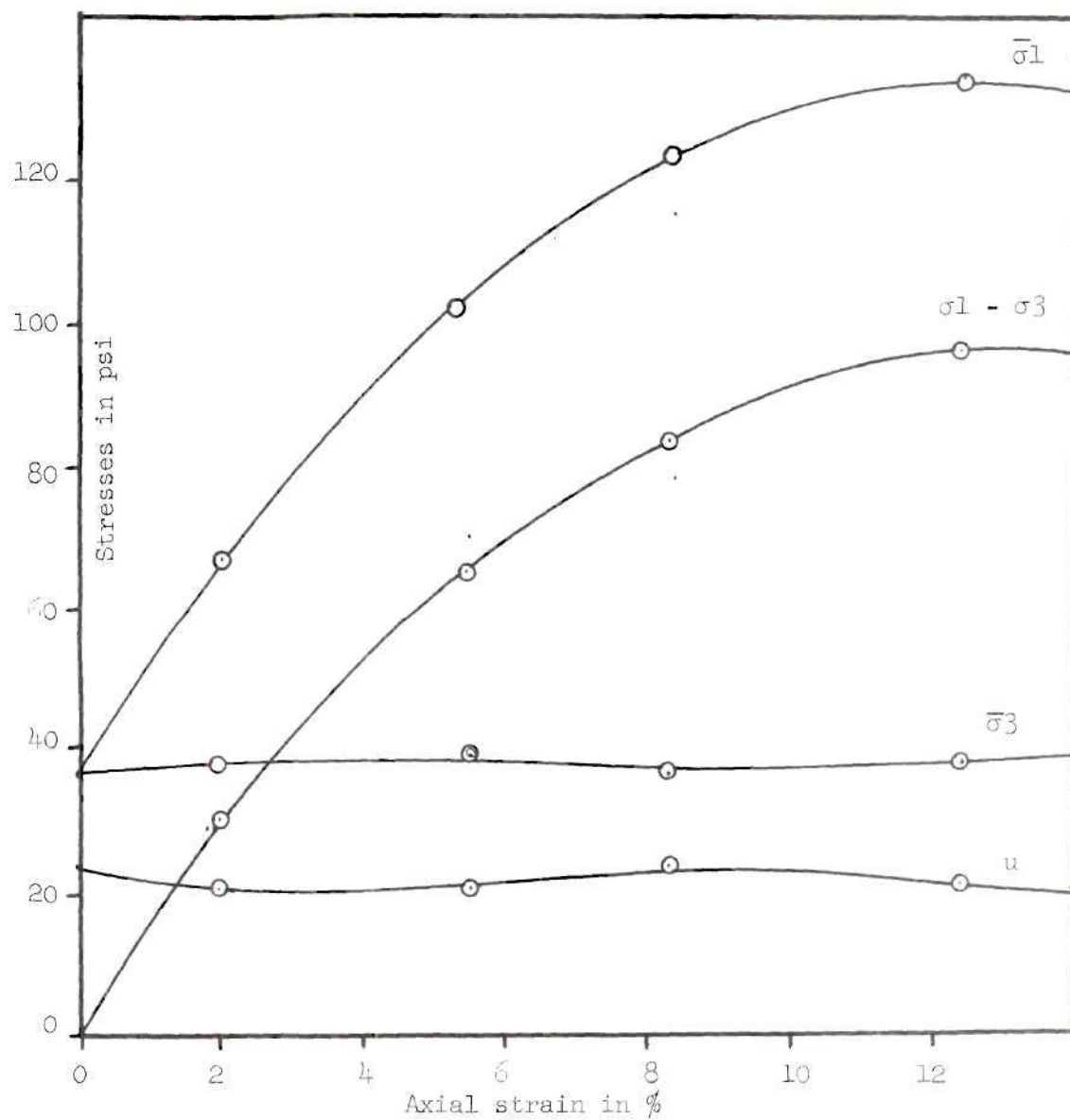


Figure 68. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 1.0
 All around Pressure: 75 psi

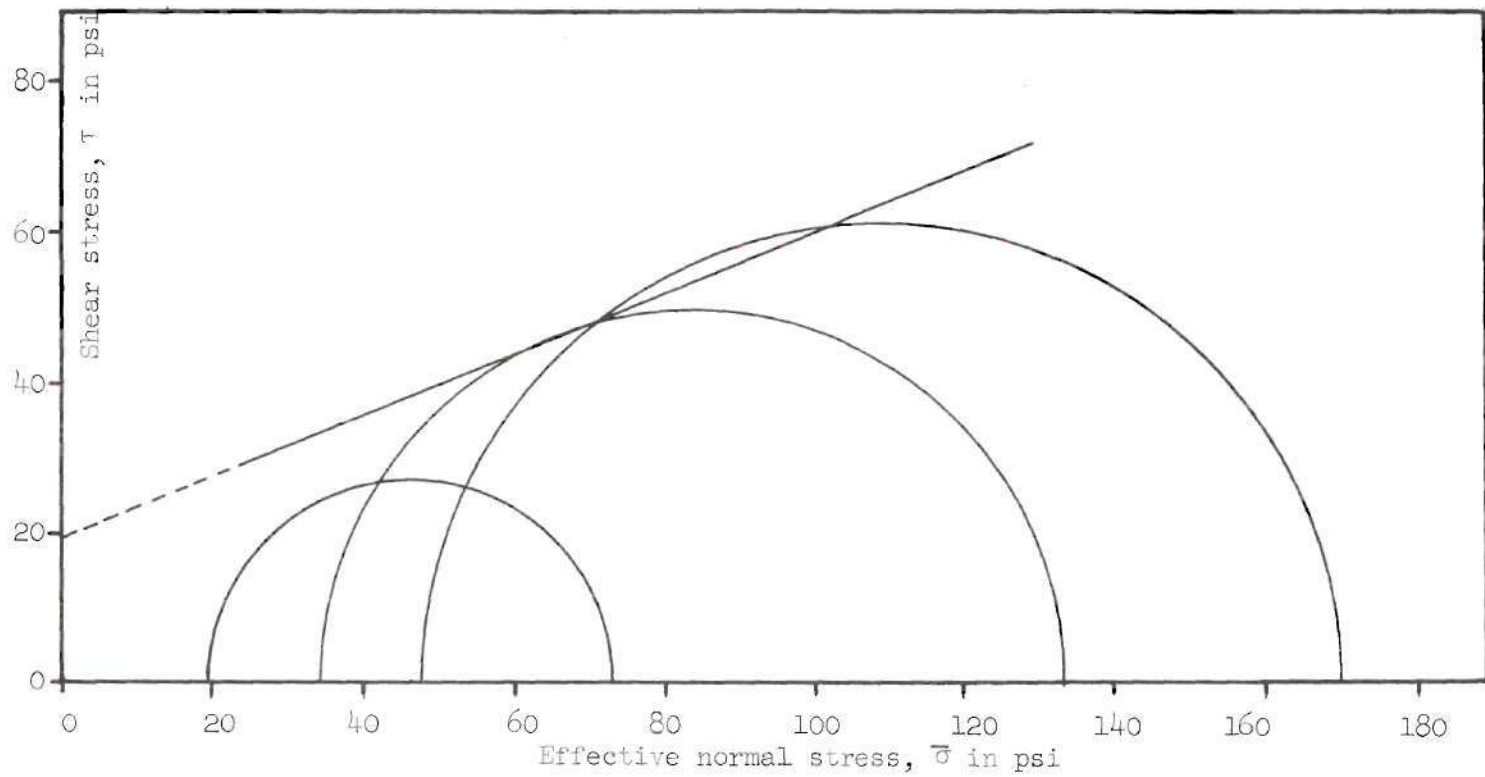


Figure 69. Mohr Circles
 Admixture: Polytergent LF-405
 Percent Admixture: 1.0

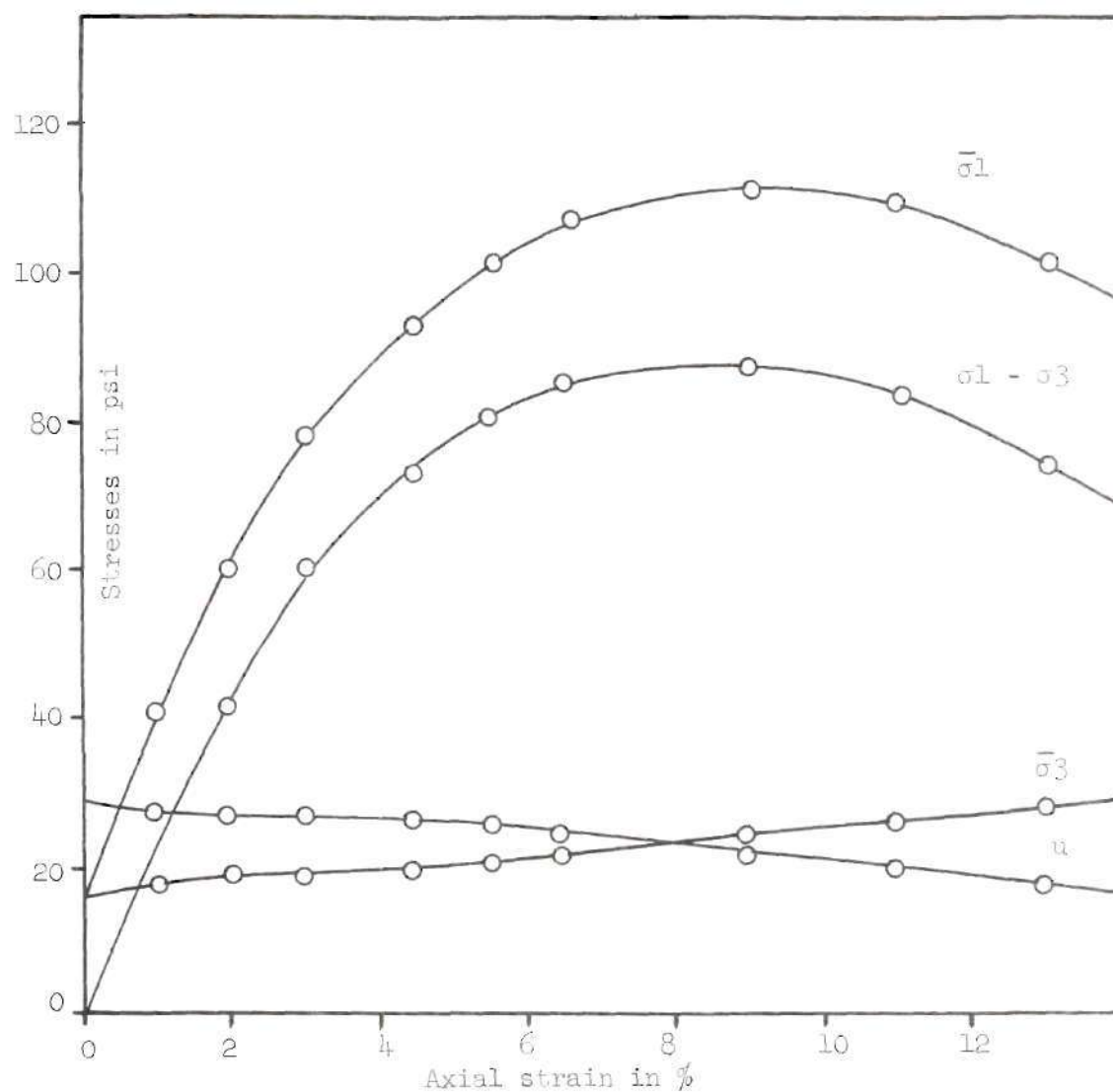


Figure 70. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 2.0
 All around Pressure: 45 psi

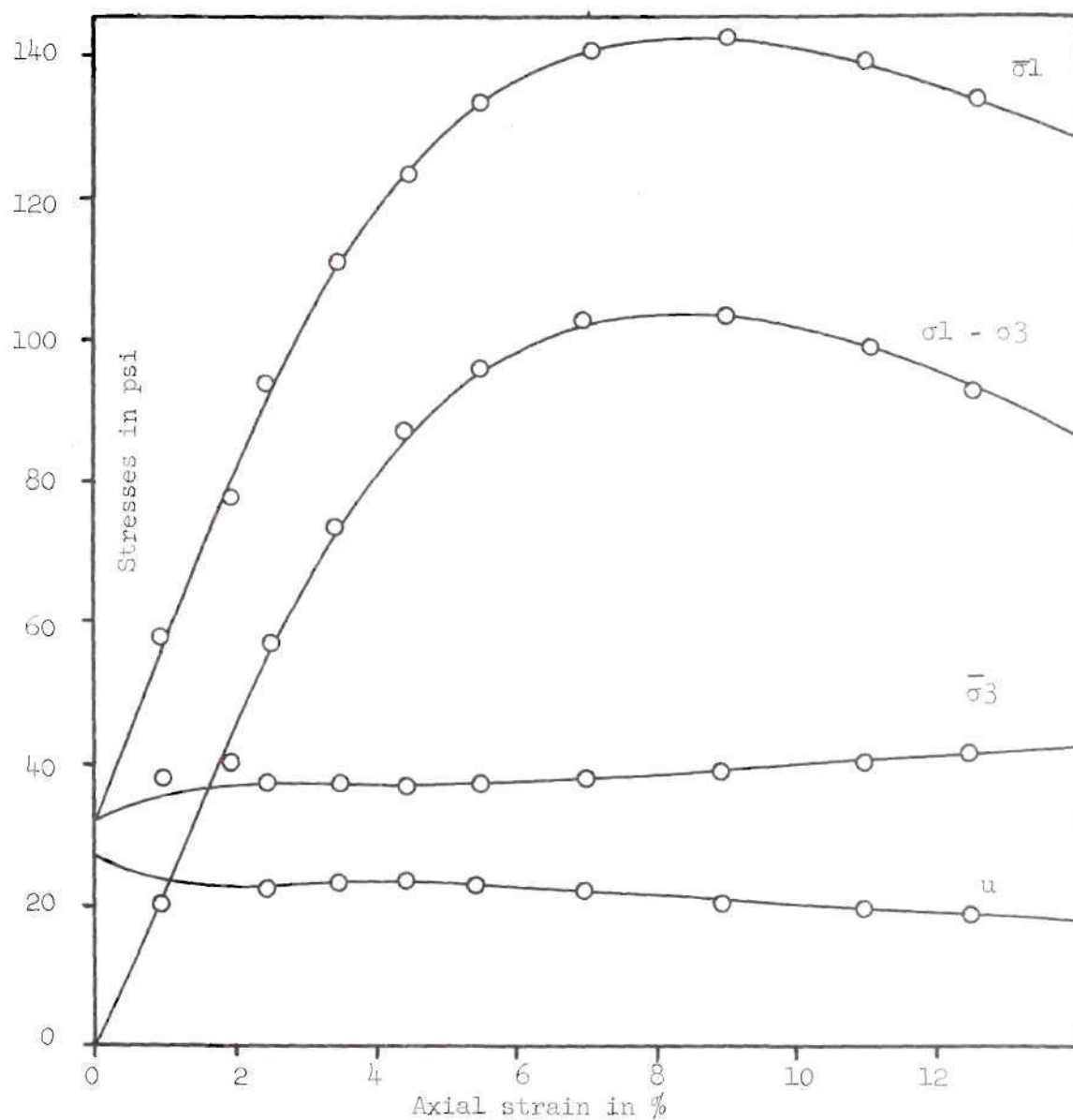


Figure 71. Triaxial Compression Test
Admixture: Polytergent LF-405
Percent Admixture: 2.0
All around Pressure: 60 psi

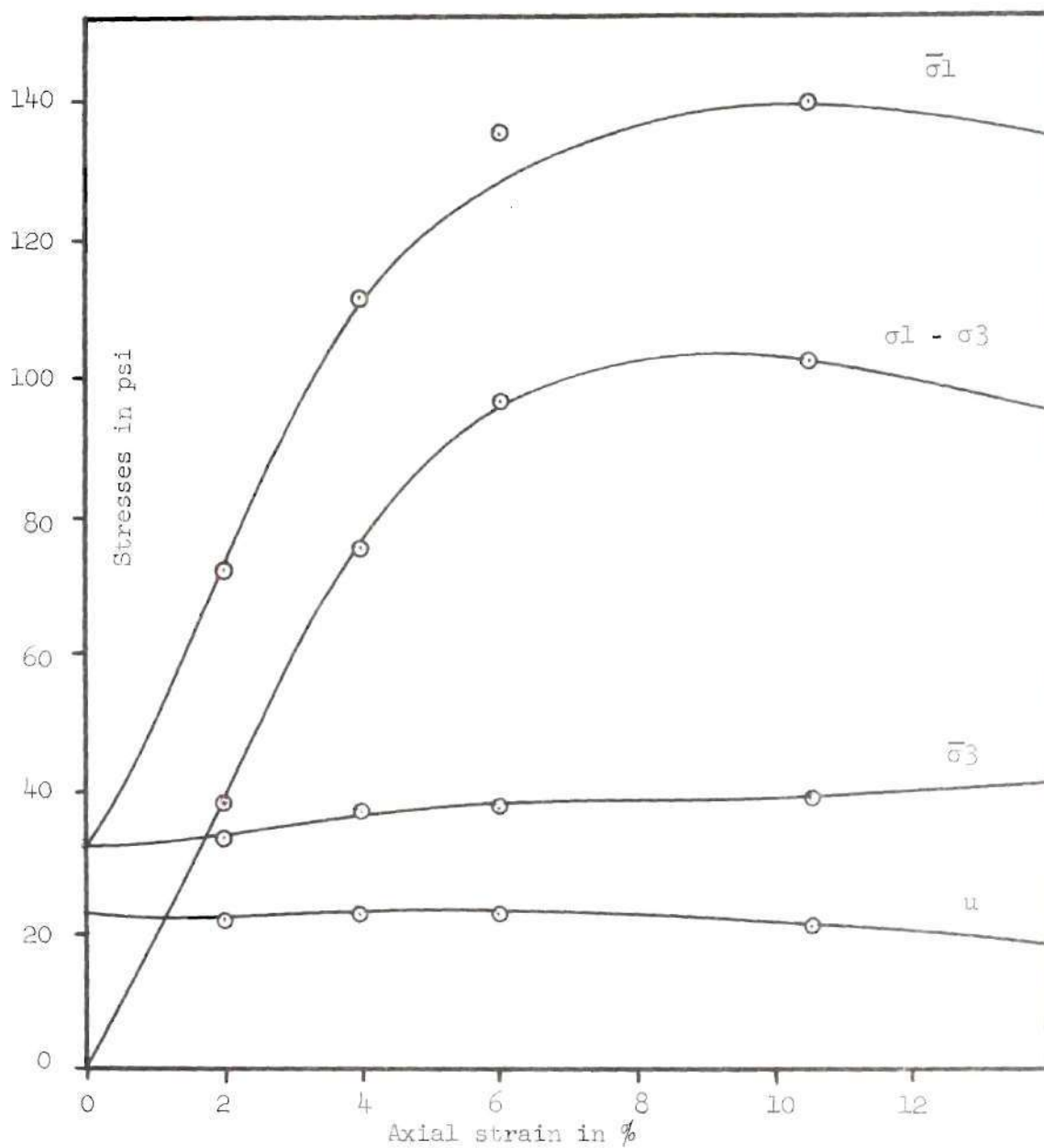


Figure 72. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 2.0
 All around Pressure: 75 psi

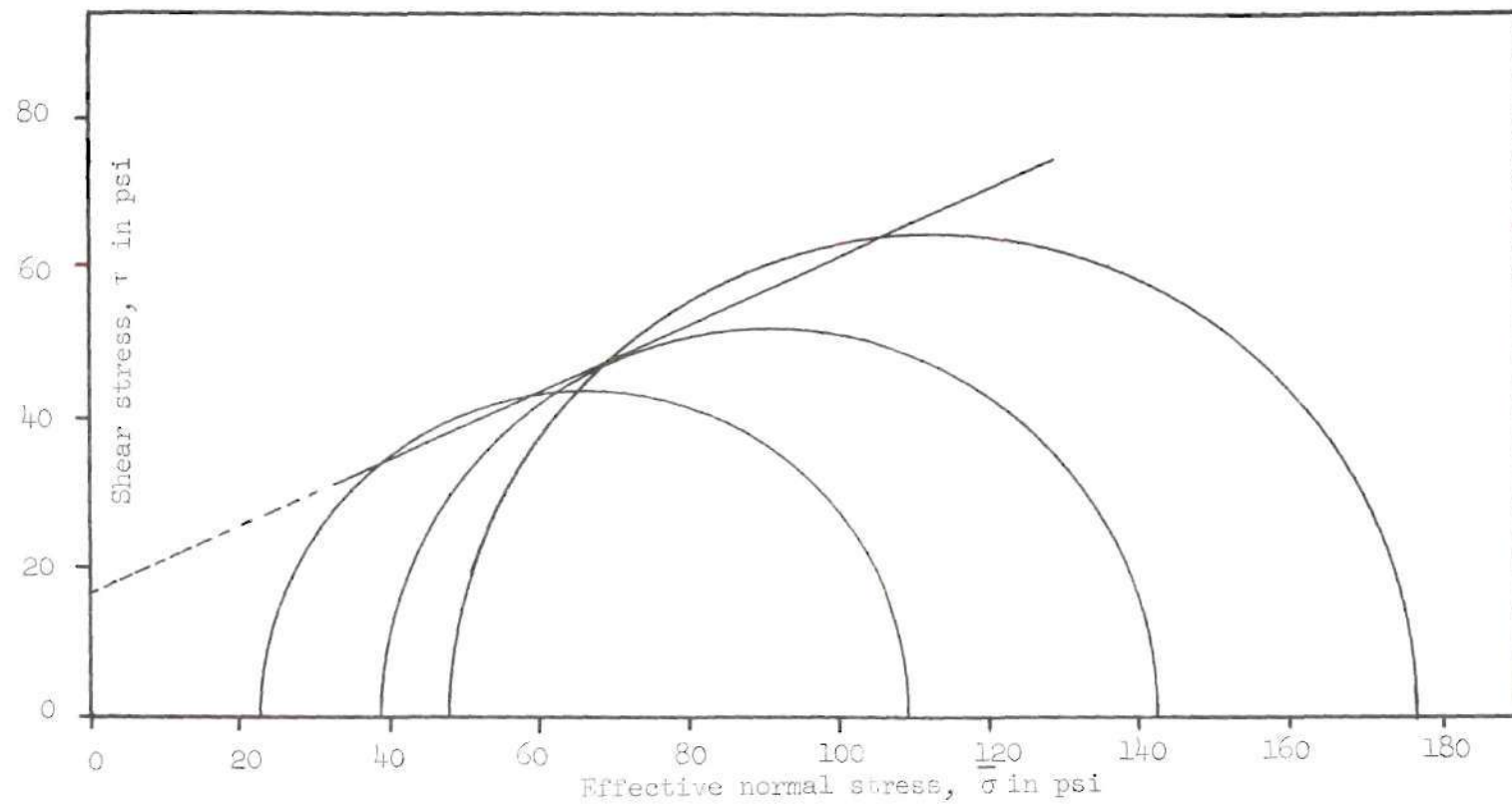


Figure 73. Mohr Circles
 Admixture: Polytargent LF-405
 Percent Admixture: 2.0

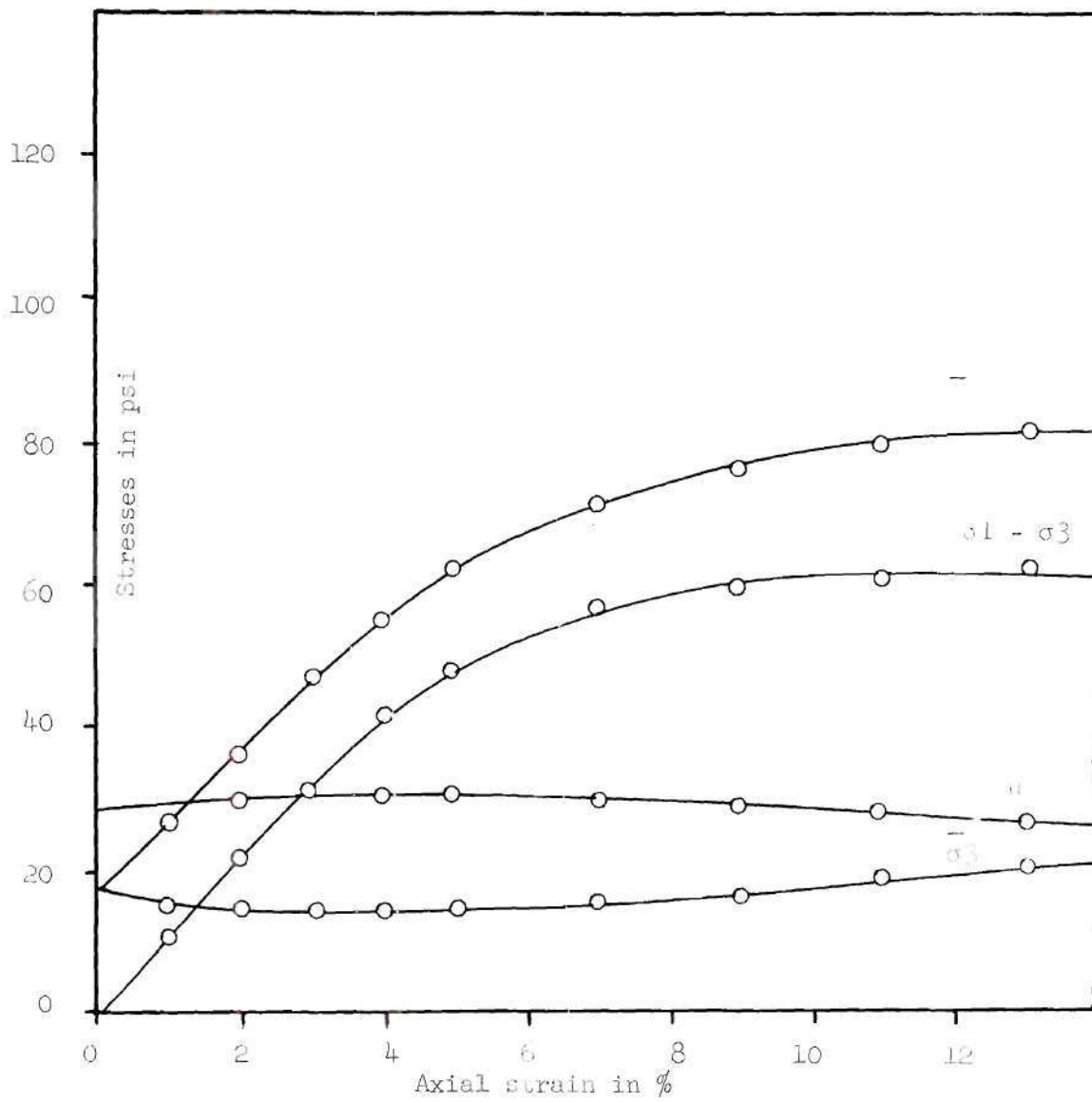


Figure 74. Triaxial Compression Test
 Admixture: Polytergen LF-405
 Percent Admixture: 3.0
 All around Pressure: 45 psi

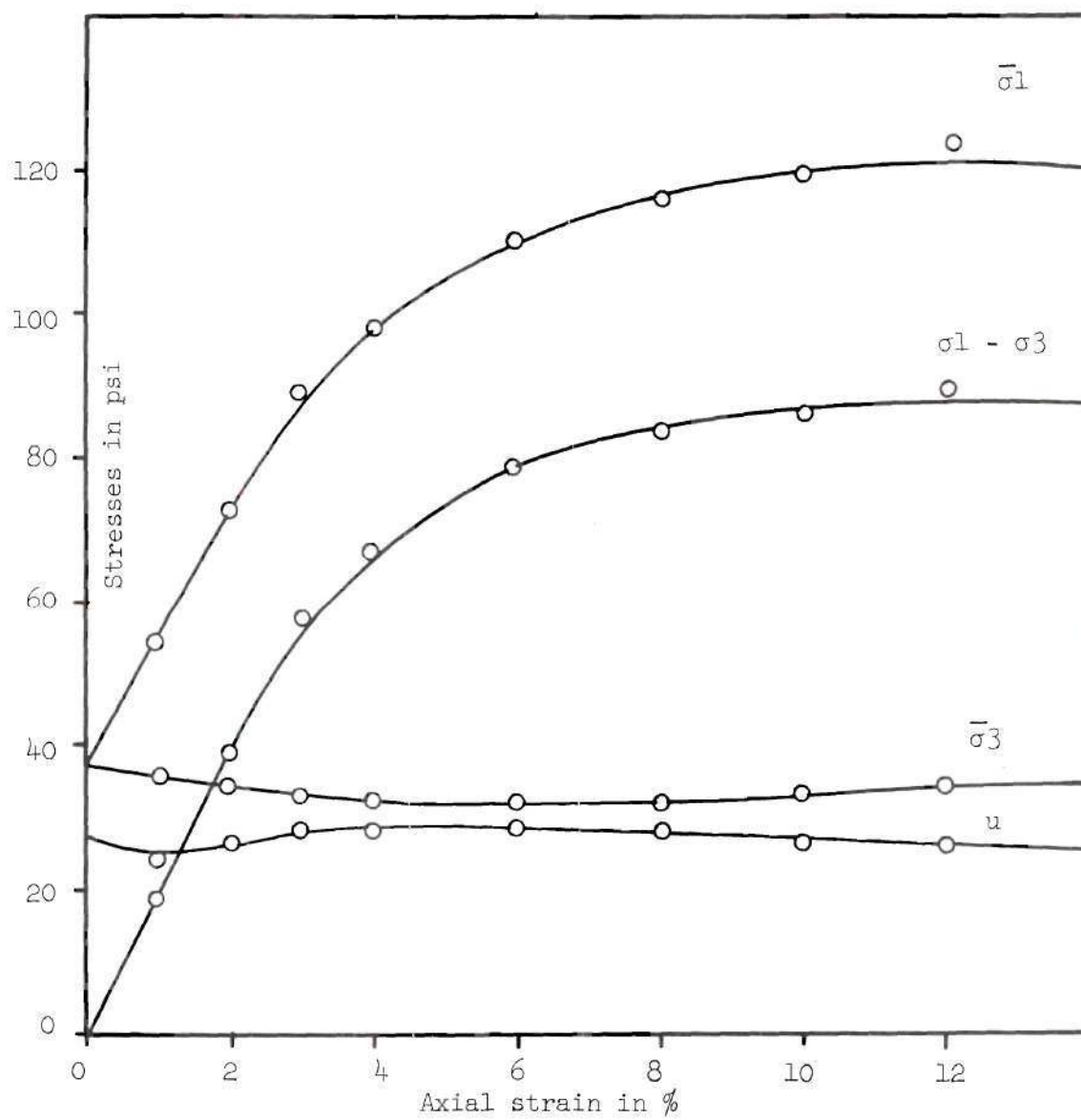


Figure 75. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 3.0
 All around pressure: 60 psi

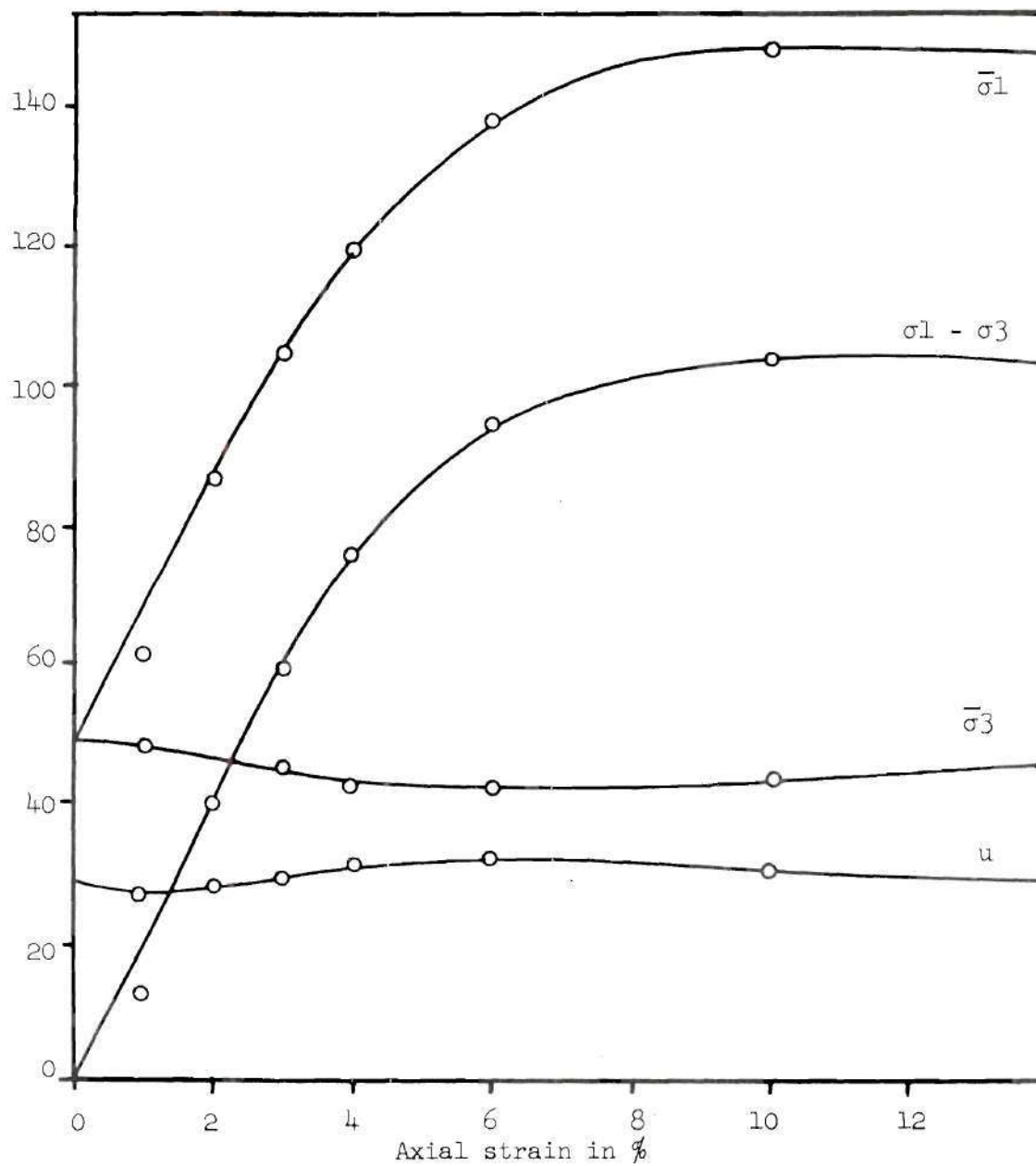


Figure 76. Triaxial Compression Test
 Admixture: Polytergent LF-405
 Percent Admixture: 3.0
 All around Pressure: 75 psi

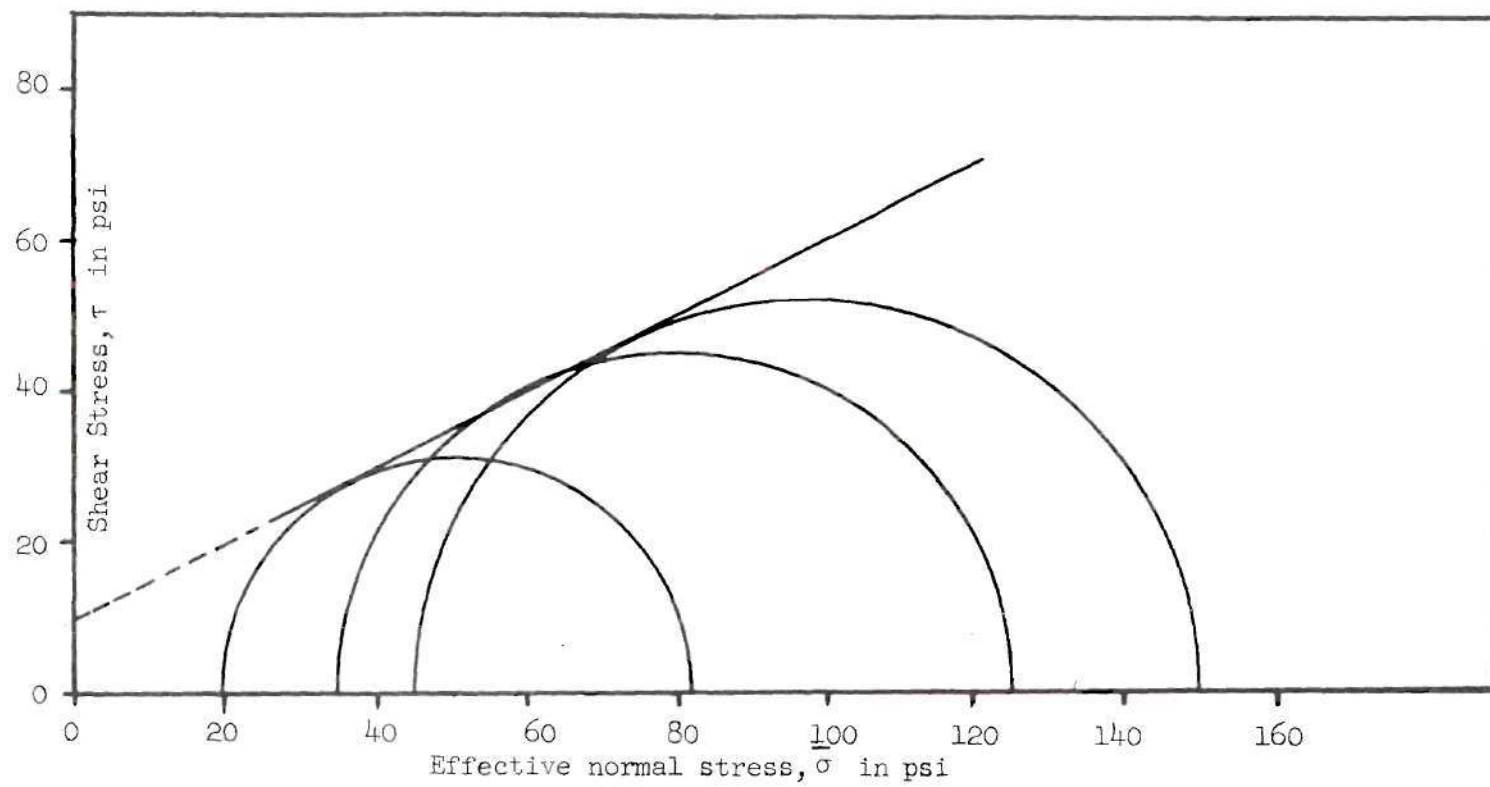


Figure 77. Mohr Circles
Admixture: Polytergent LF-405
Percent Admixture: 3.0

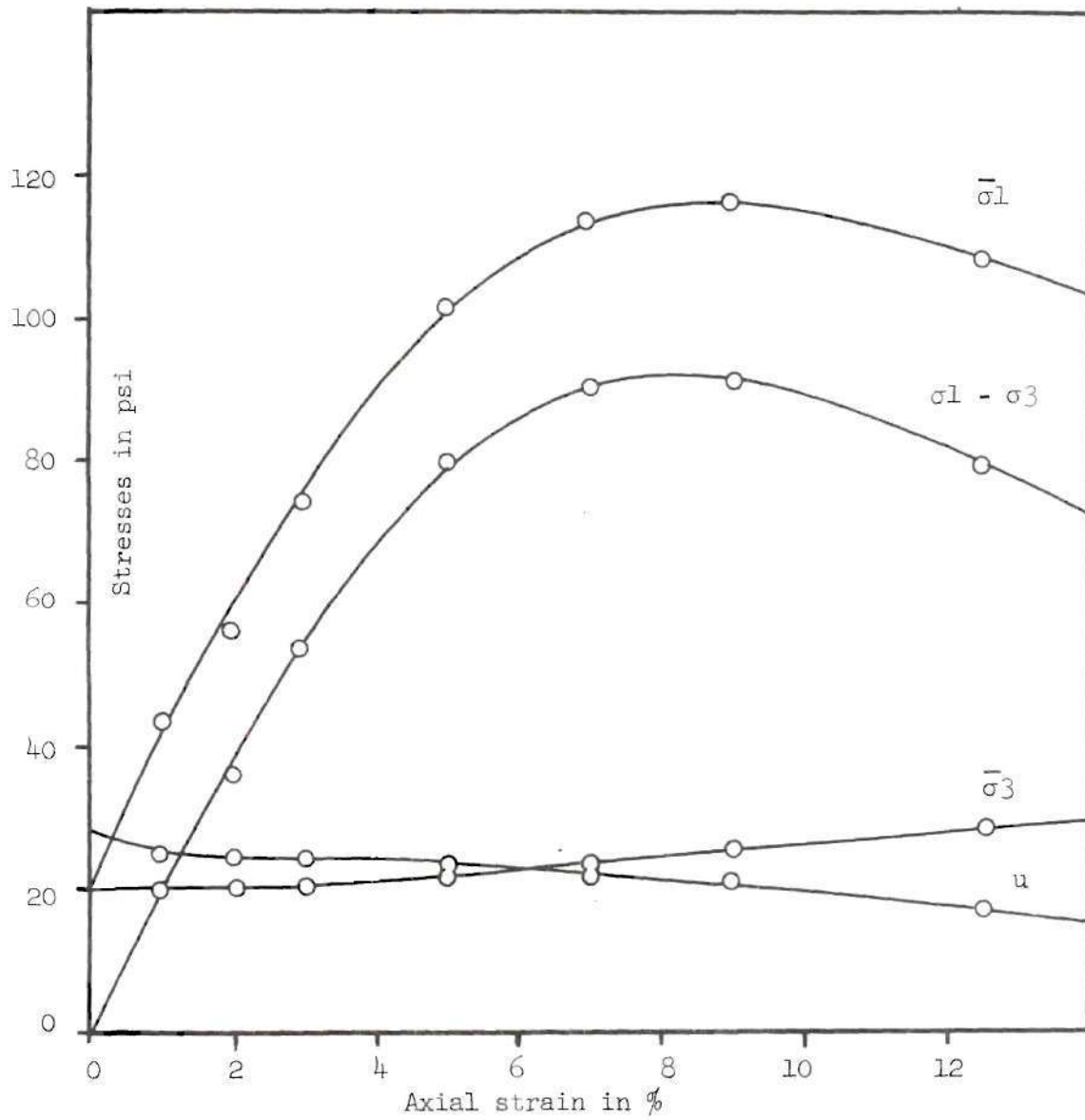


Figure 78. Triaxial Compression Test.
 Admixture: Alkanol B
 Percent Admixture: 0.25
 All around Pressure: 45 psi

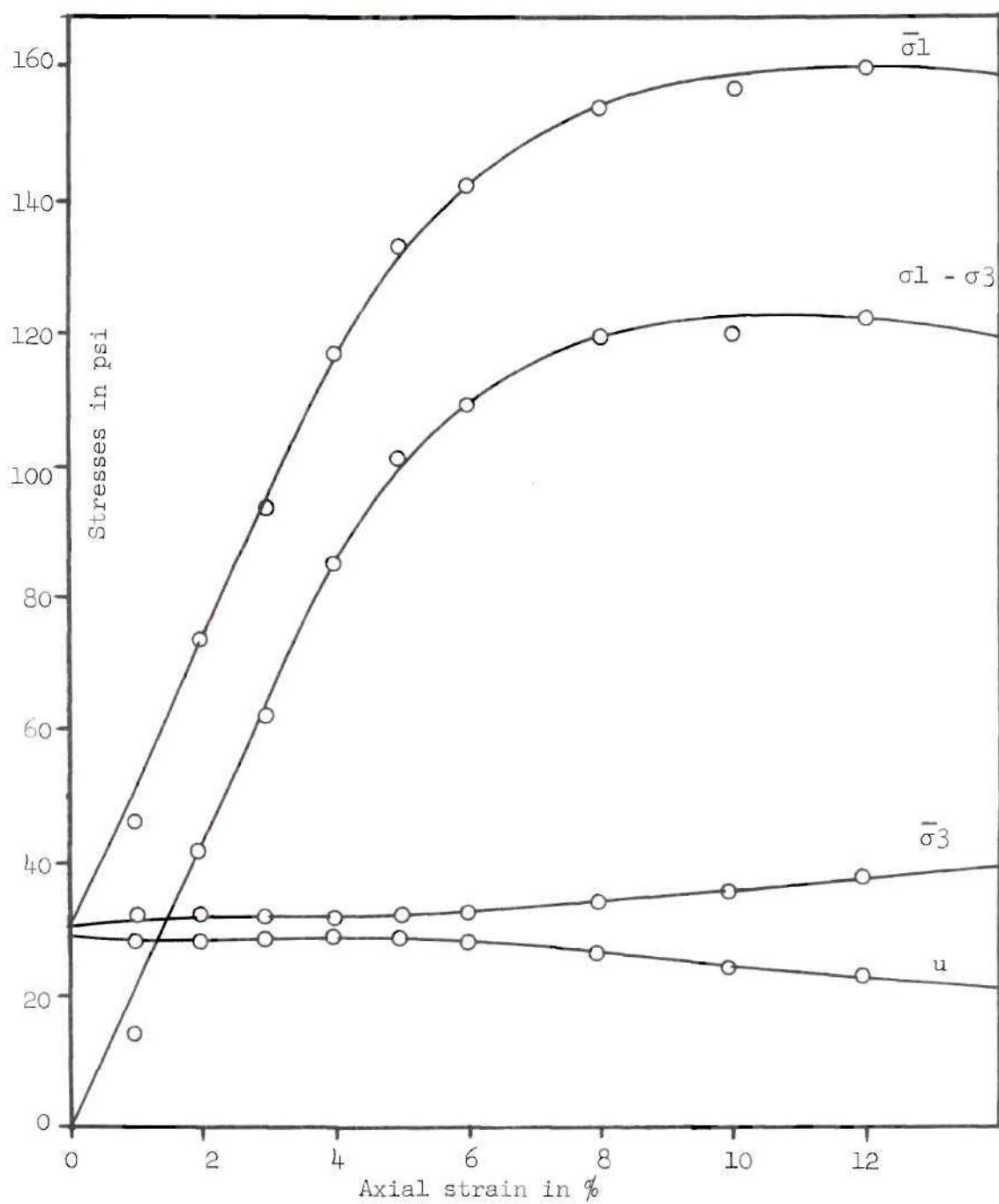


Figure 79. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 0.25
 All around Pressure: 60 psi

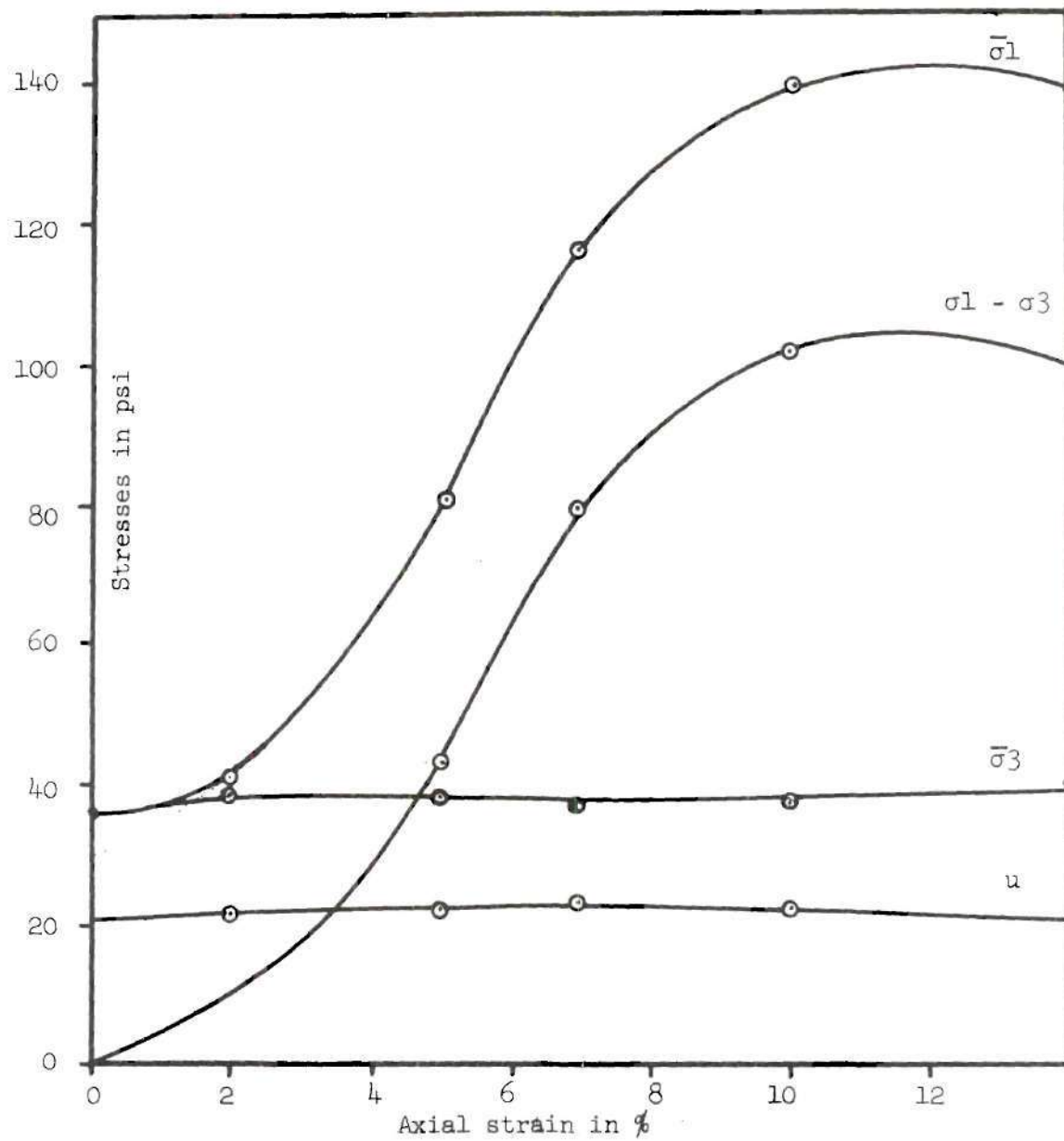


Figure 80. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 0.25
 All around Pressure: 75 psi

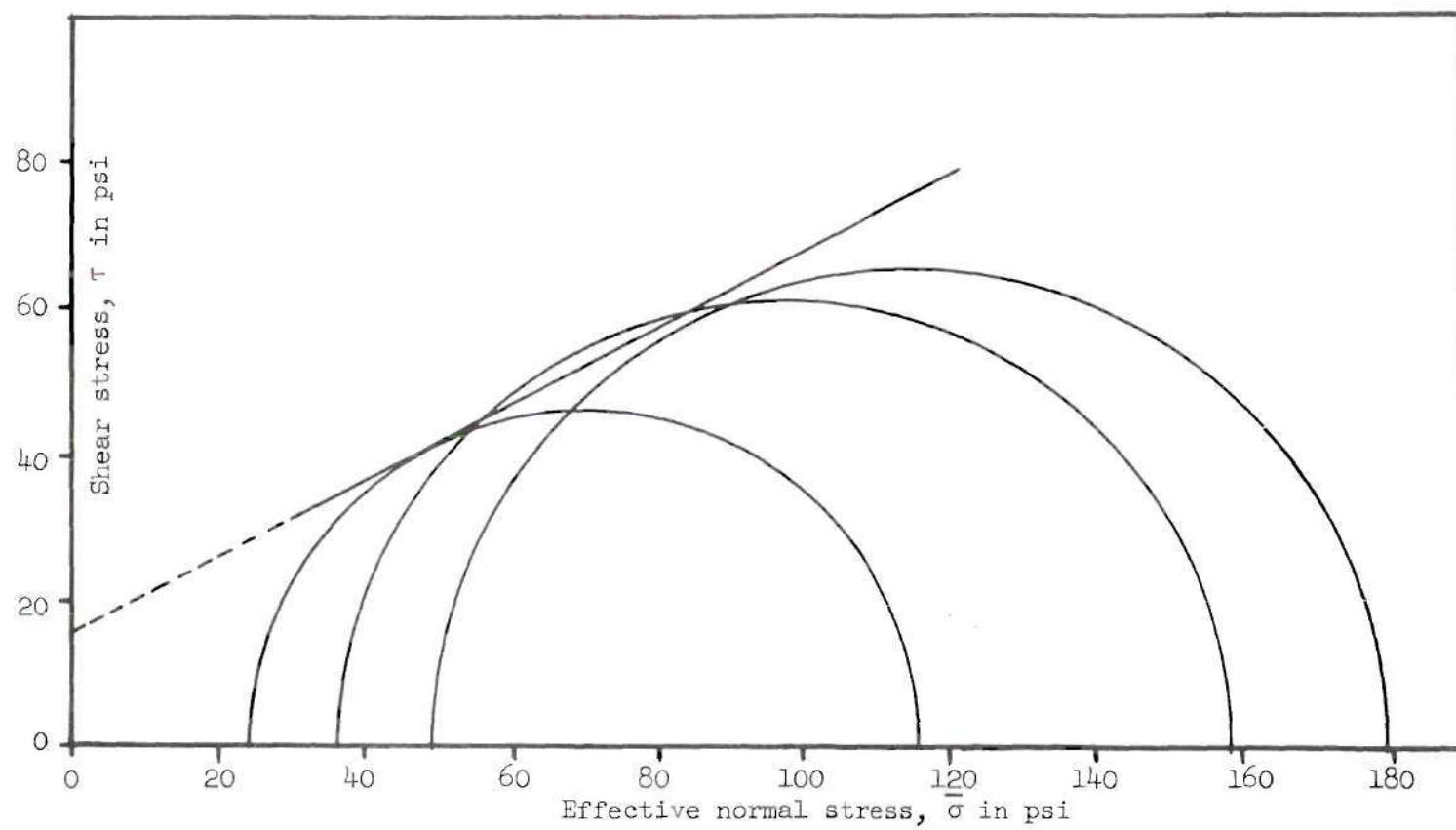


Figure 81. Mohr Circles
 Admixture: Alkanol B
 Percent Admixture: 0.25

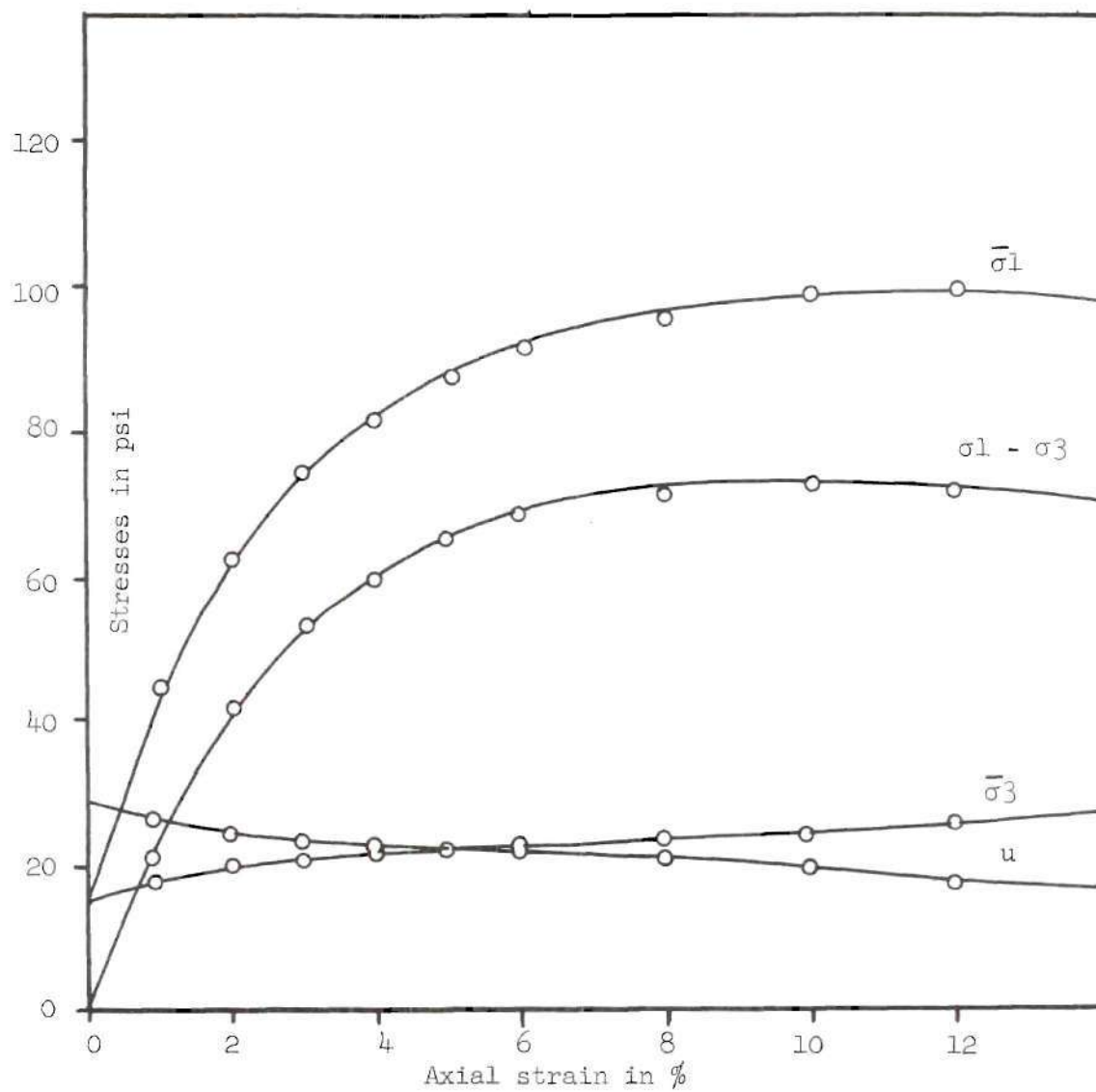


Figure 82: Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 0.5
 All around Pressure: 45 psi

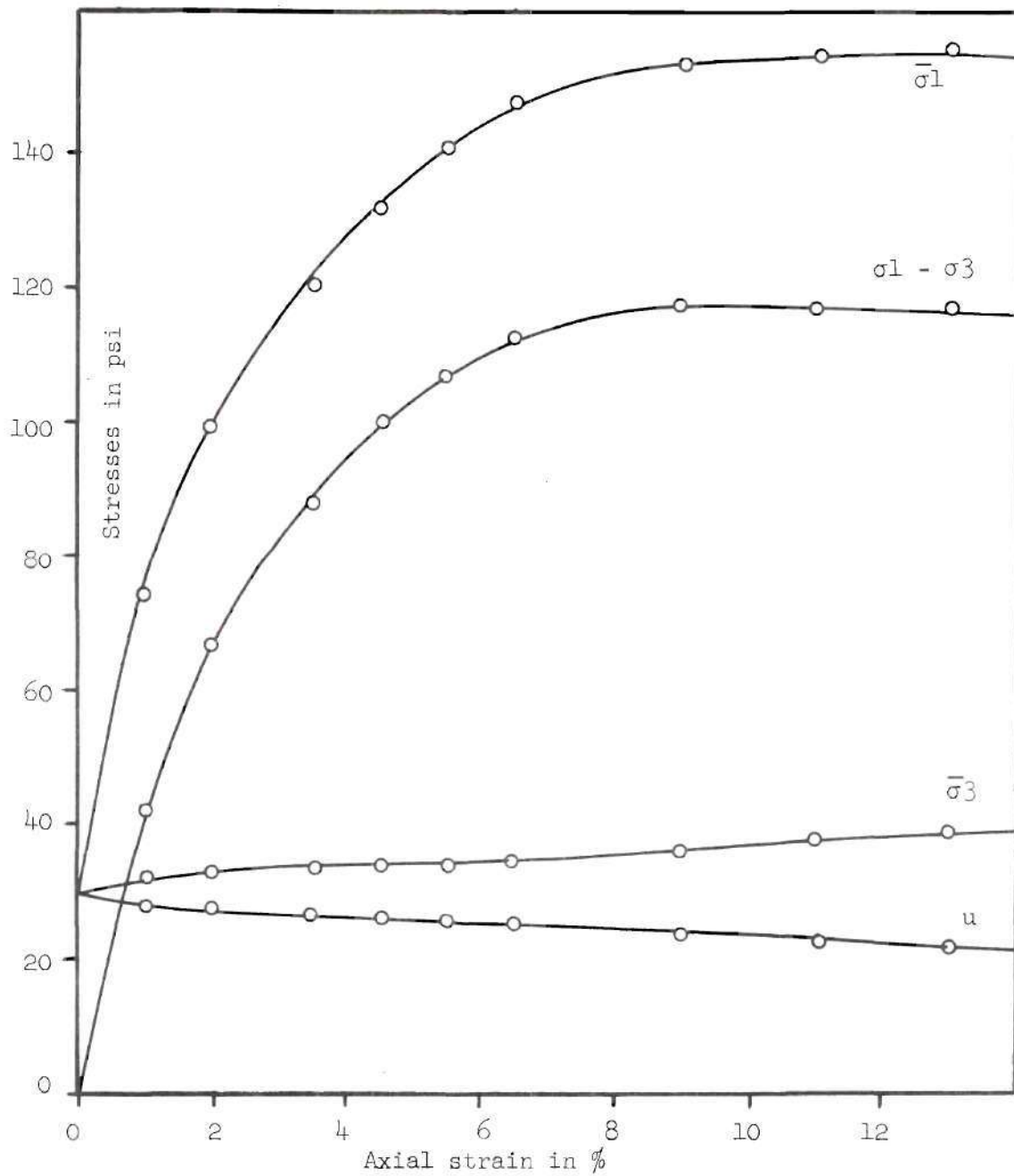


Figure 83. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 0.5
 All around Pressure: 60 psi

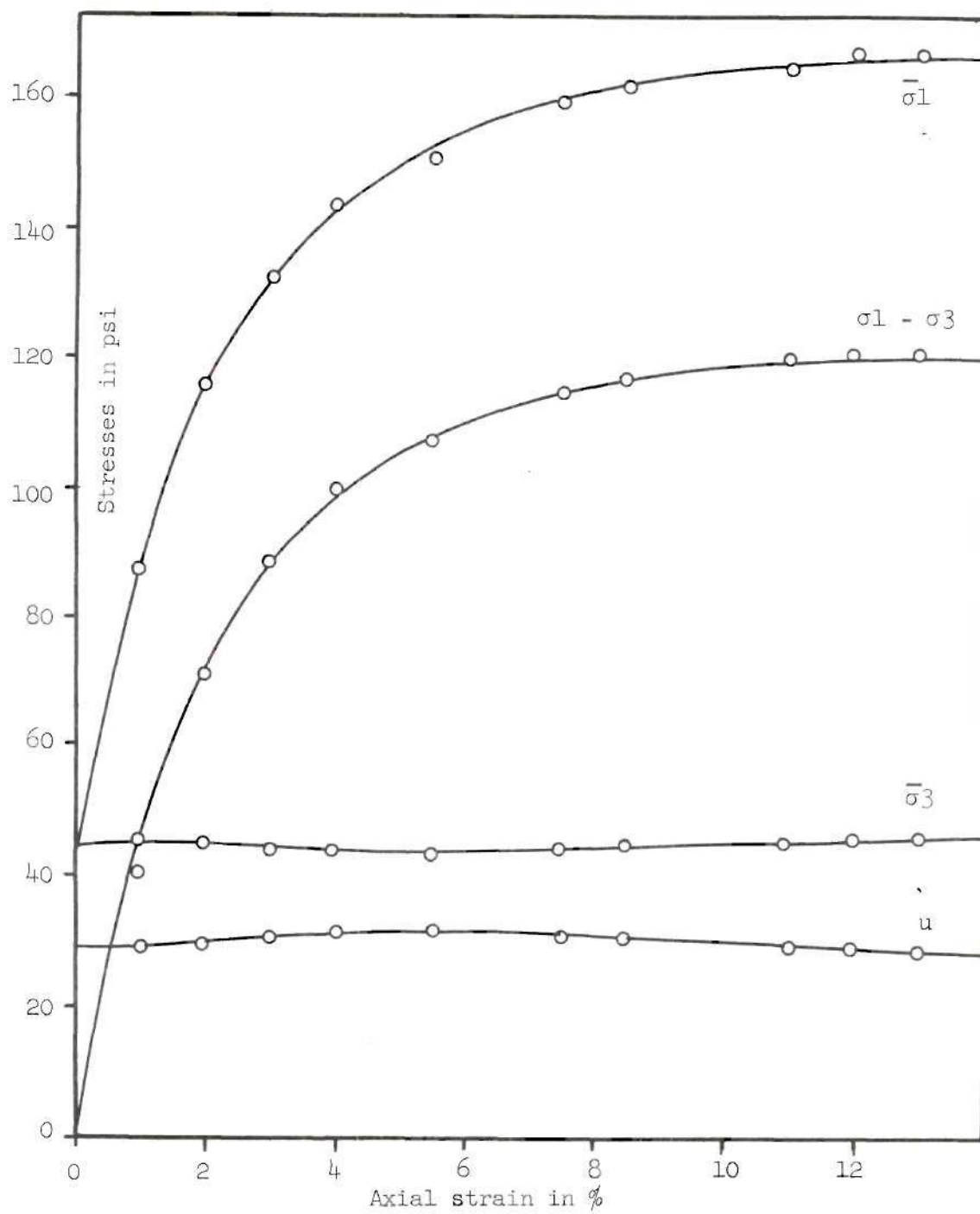


Figure 84. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 0.5
 All around Pressure: 75 psi

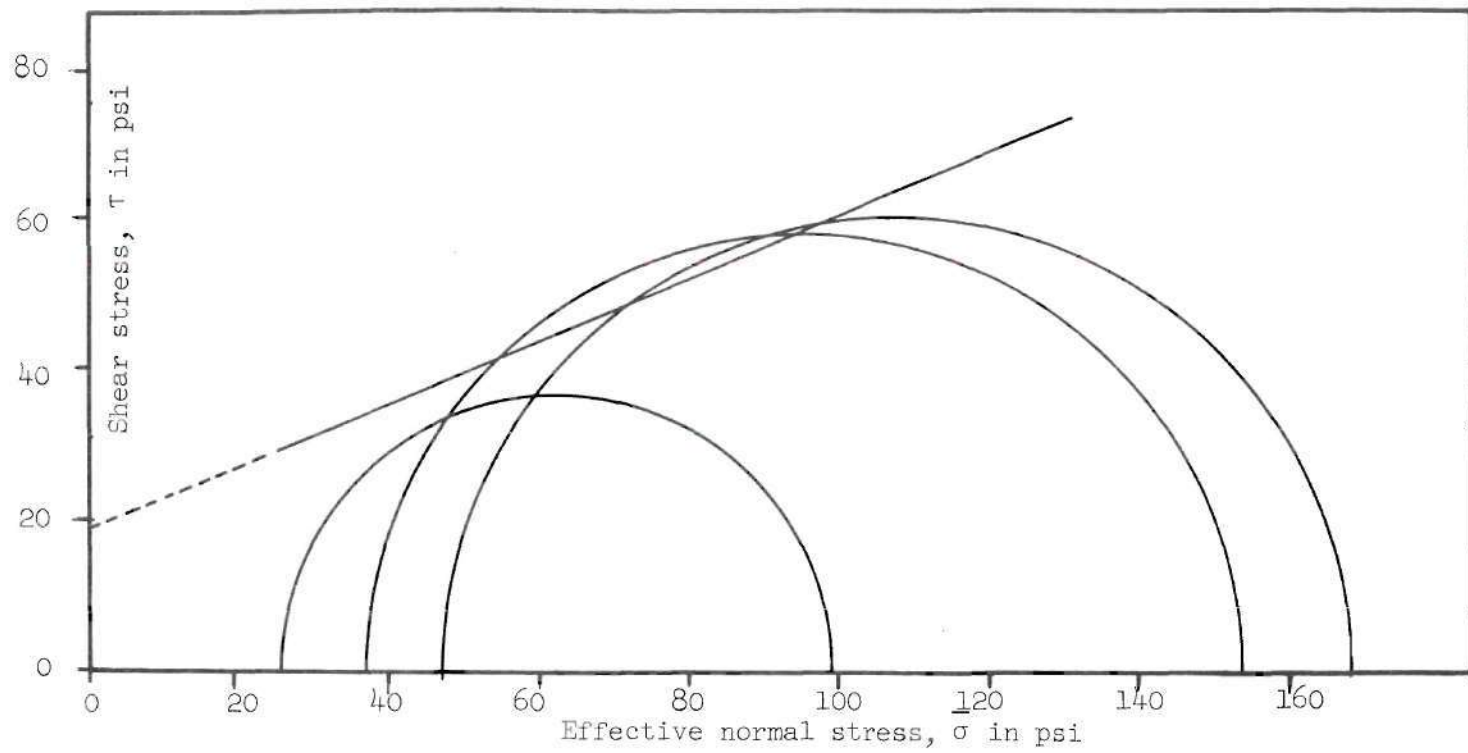


Figure 85. Mohr Circles
 Admixture: Alkanol B
 Percent Admixture: 0.5

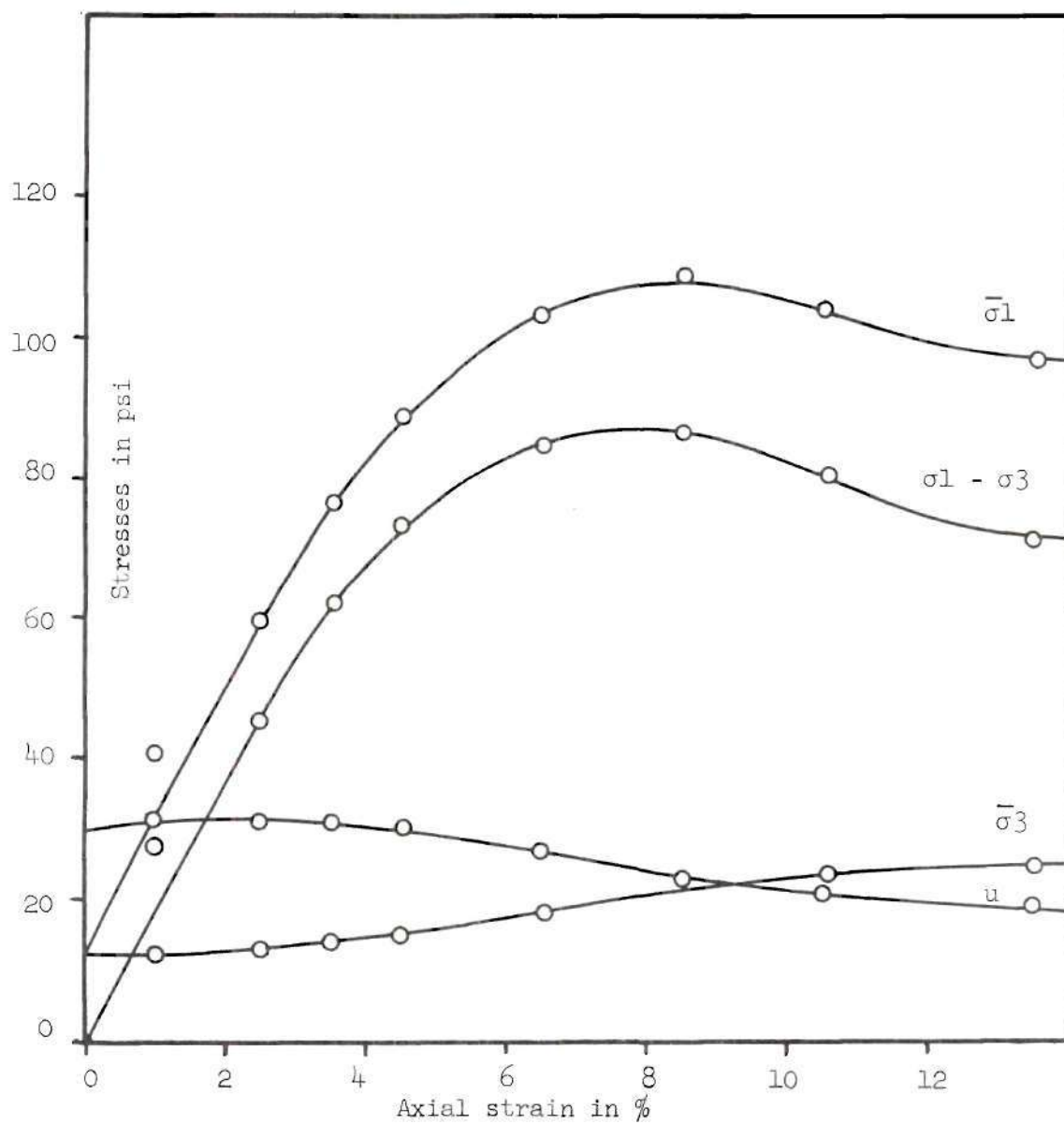


Figure 86. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 0.75
 All around Pressure: 45 psi

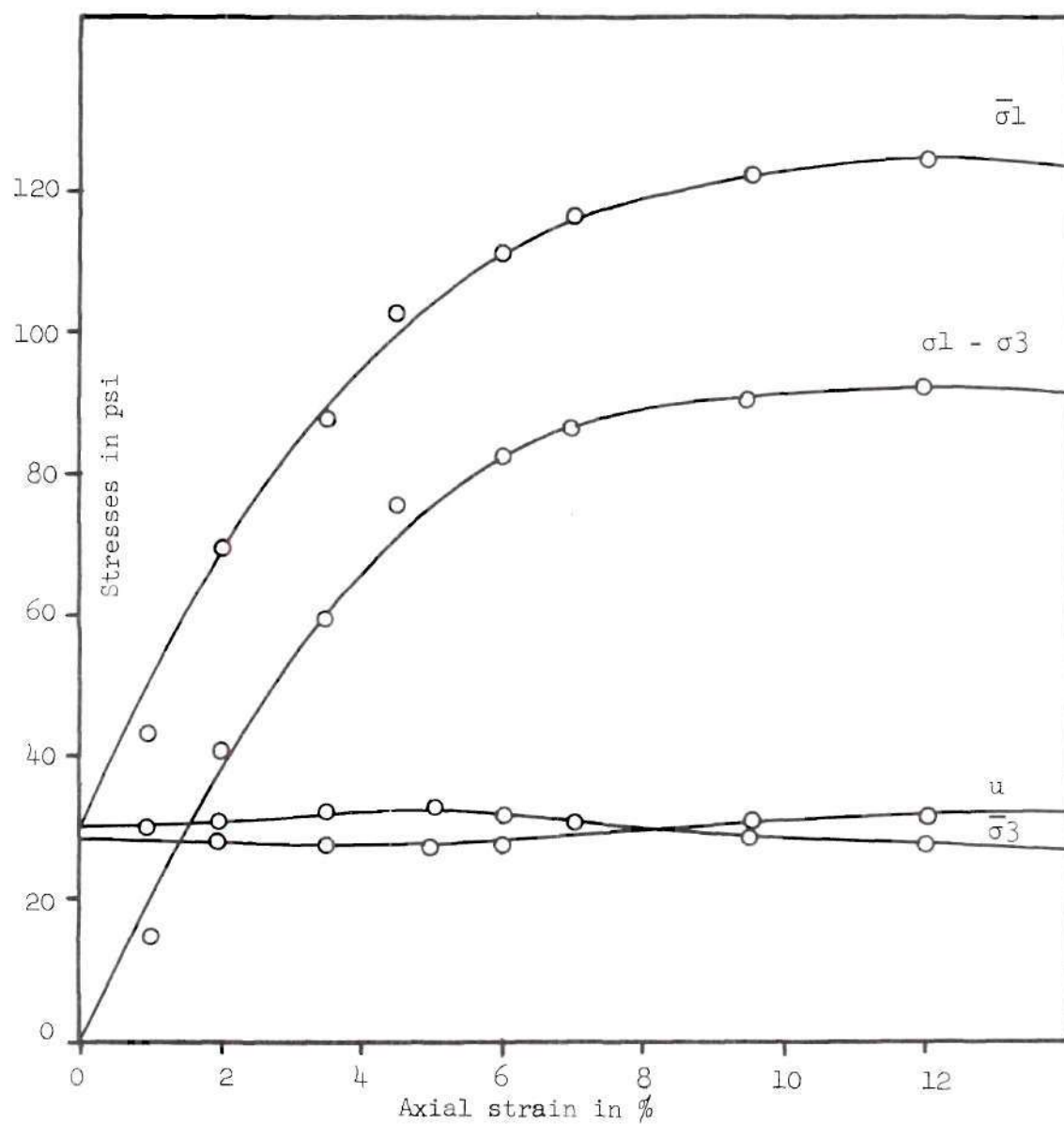


Figure 87. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 0.75
 All around Pressure: 60 psi

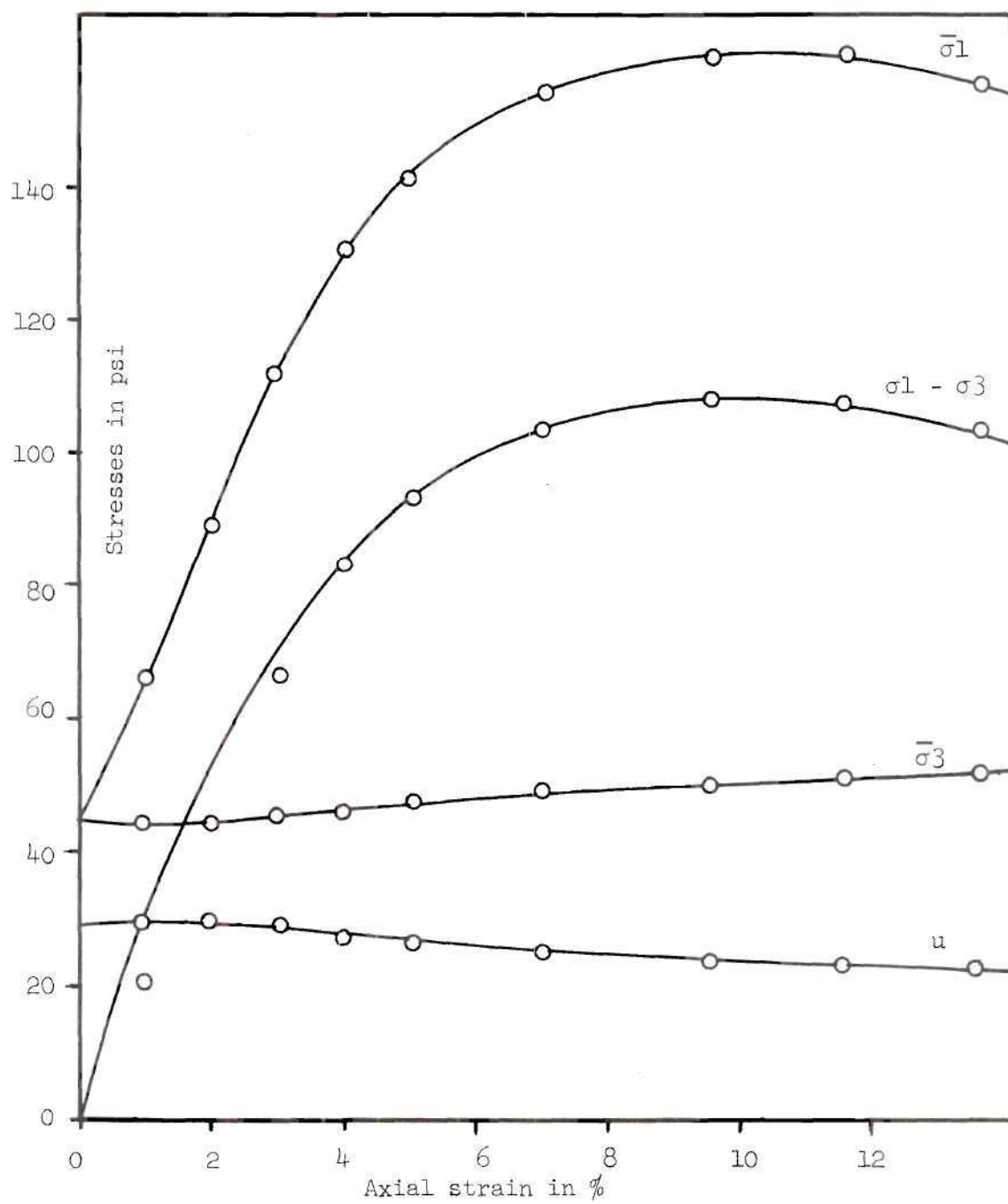


Figure 88. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 0.75
 All around Pressure: 75 psi

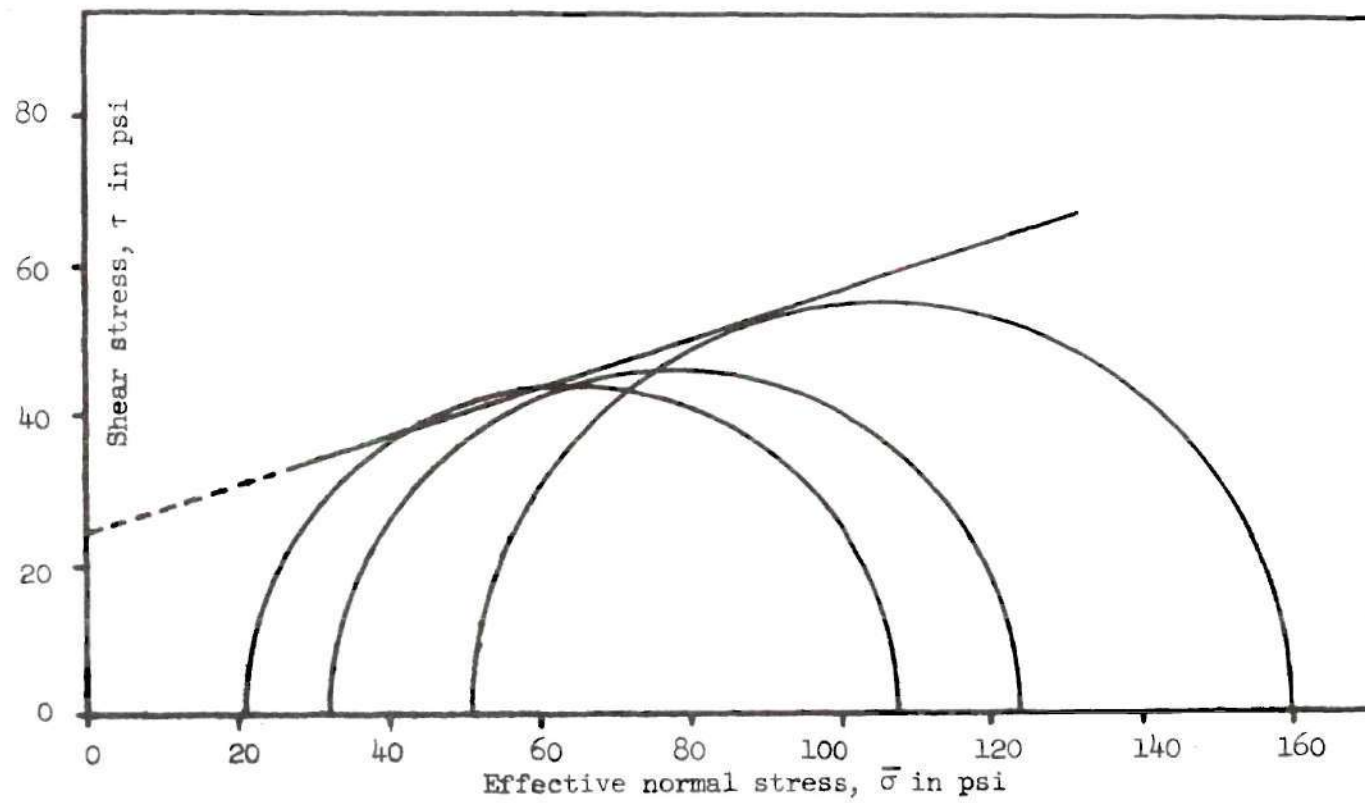


Figure 89. Mohr Circles
 Admixture: Alkanol B
 Percent Admixture: 0.75

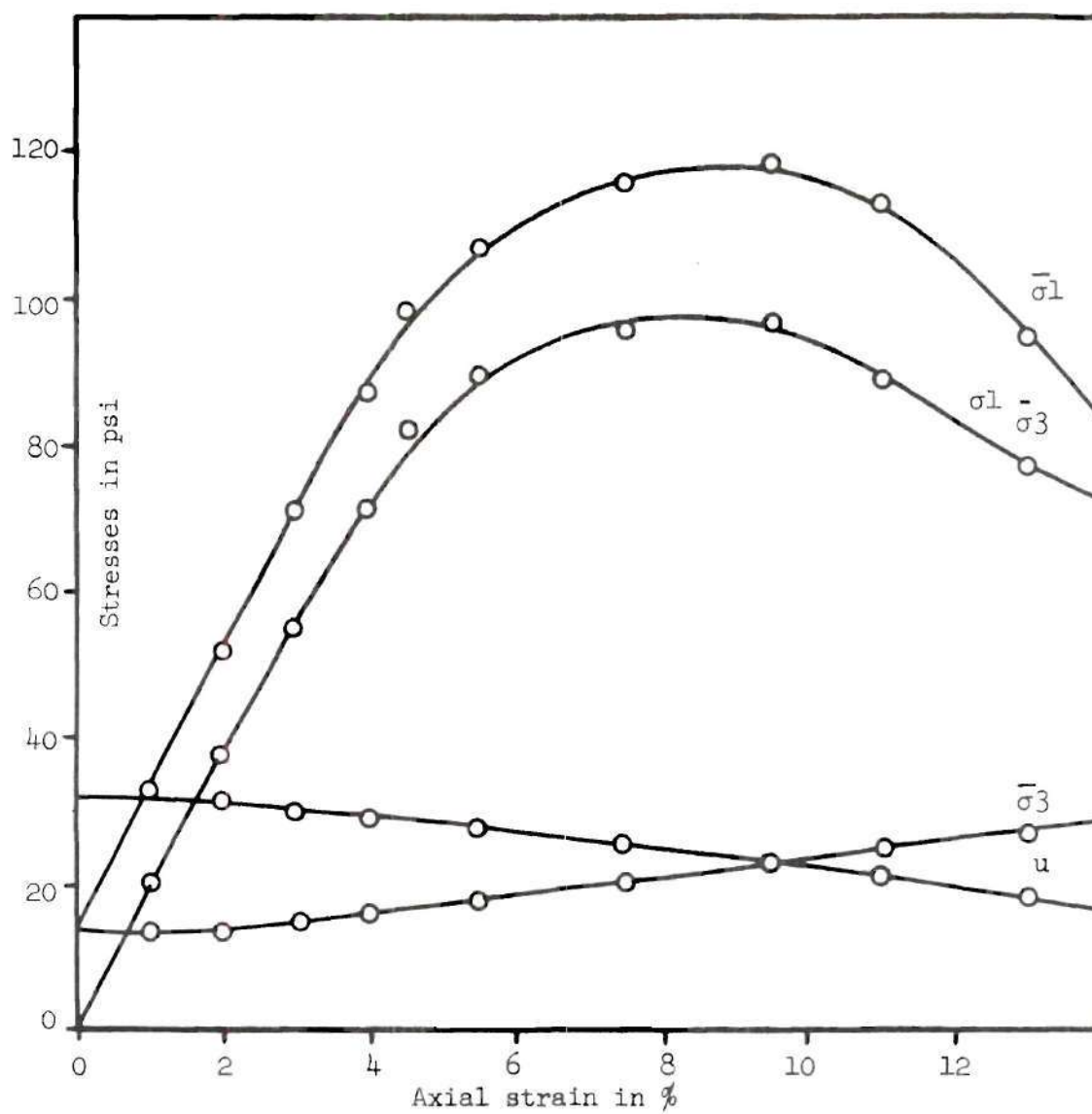


Figure 90. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 1.0
 All around Pressure: 45 psi

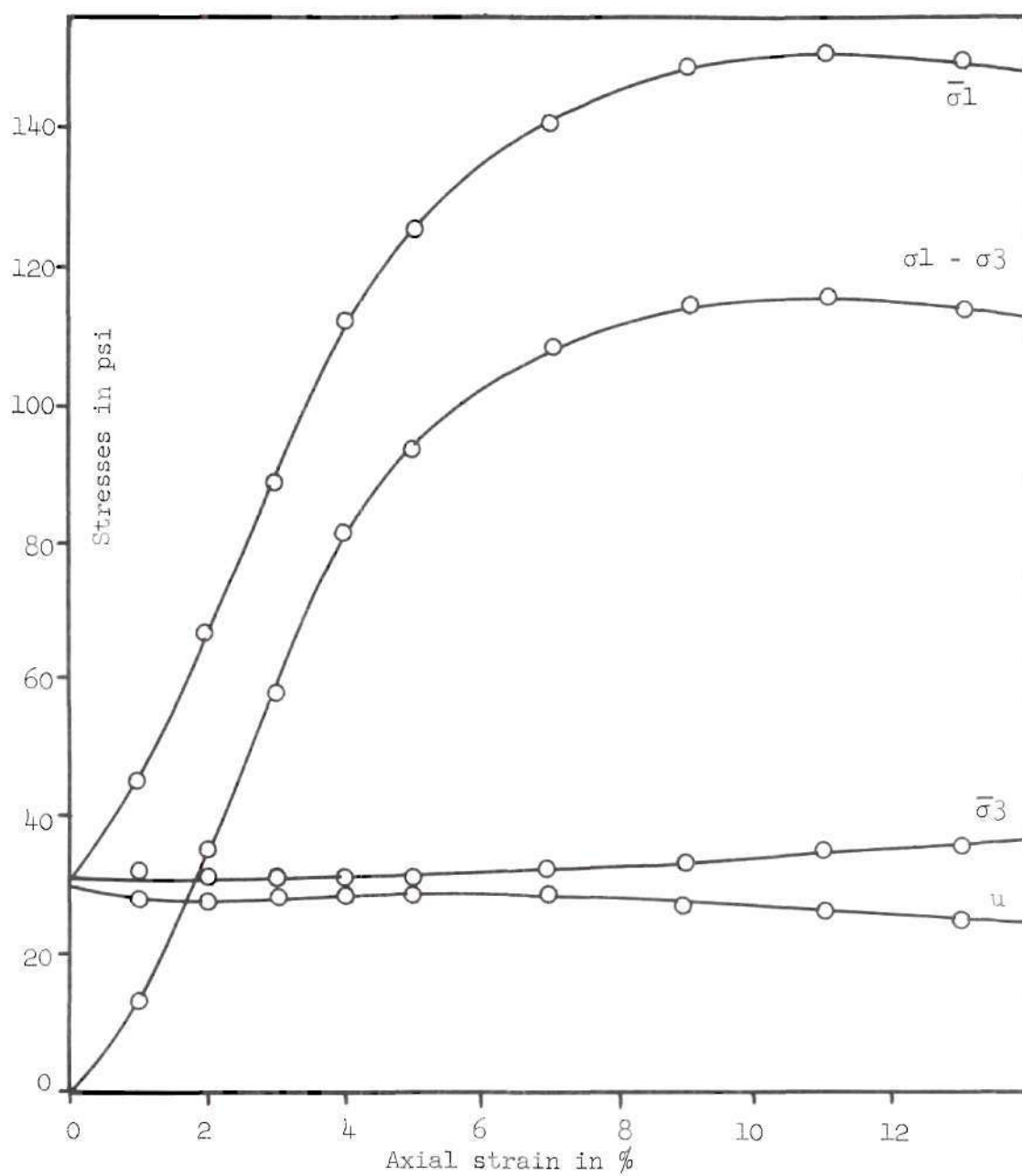


Figure 91. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 1.0
 All around Pressure: 60 psi

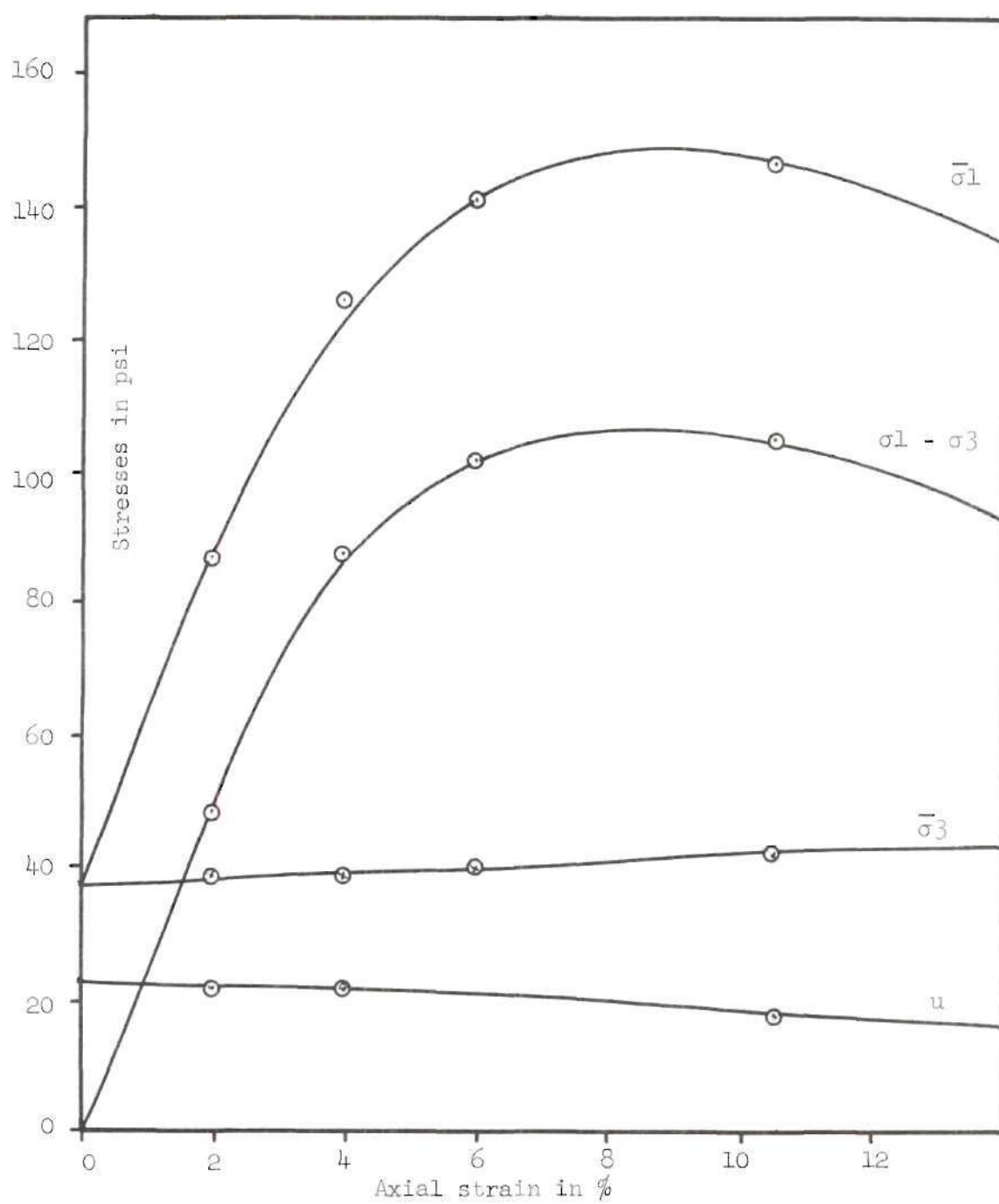


Figure 92. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 1.0
 All around Pressure: 75 psi

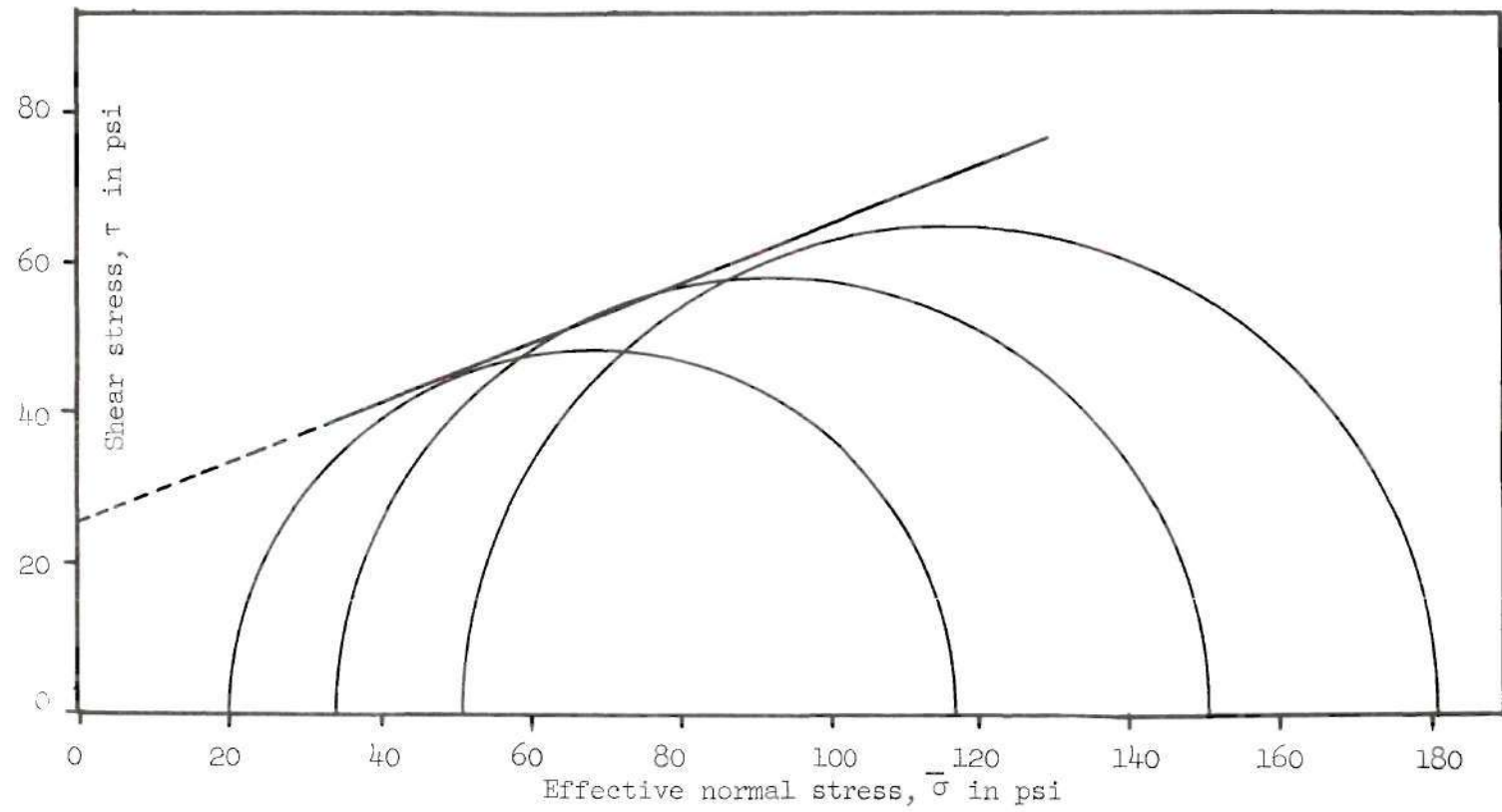


Figure 93. Mohr Circles
 Admixture: Alkanol B
 Percent Admixture: 1.0

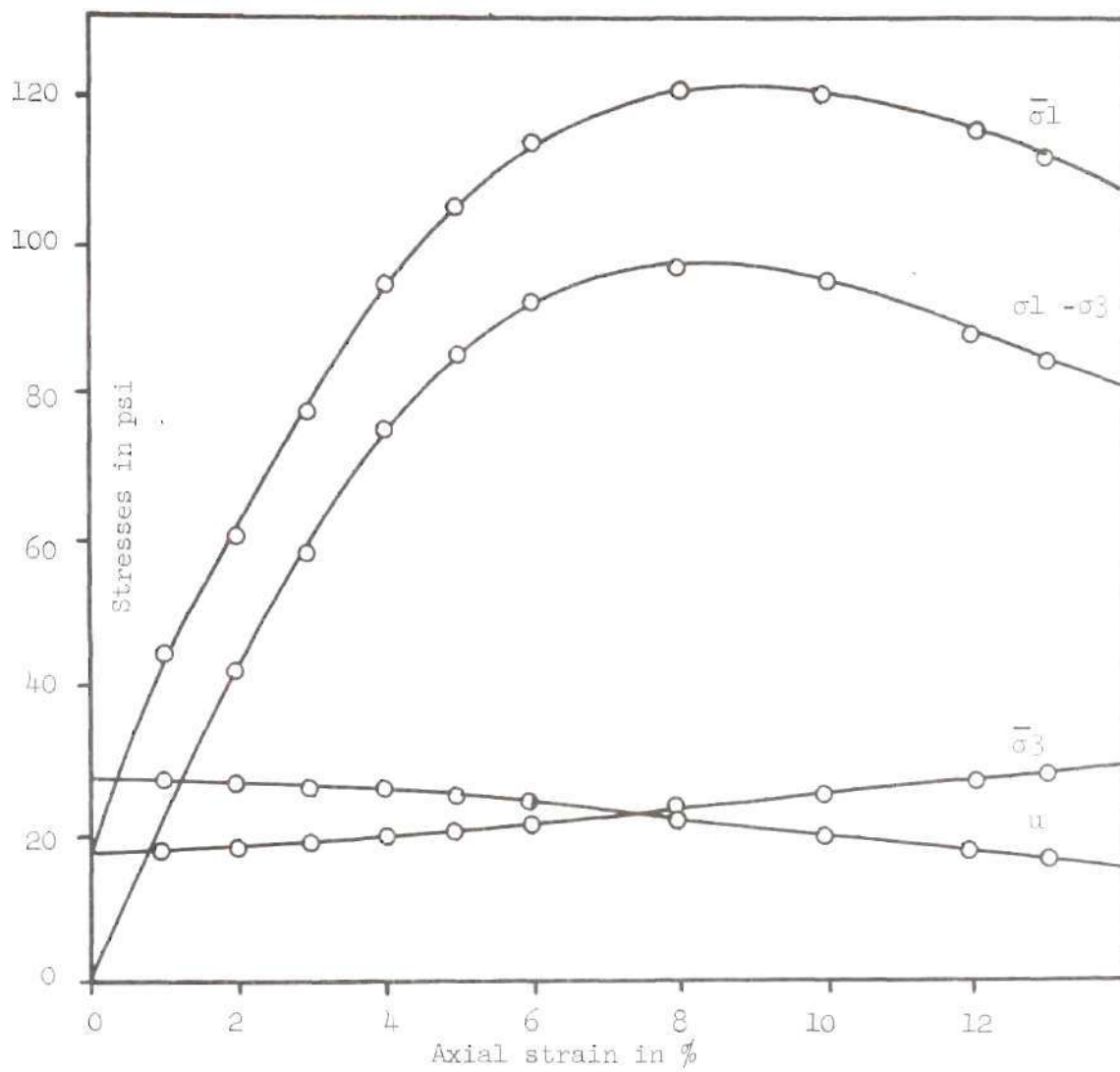


Figure 94. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 2.0
 All around Pressure: 45 psi

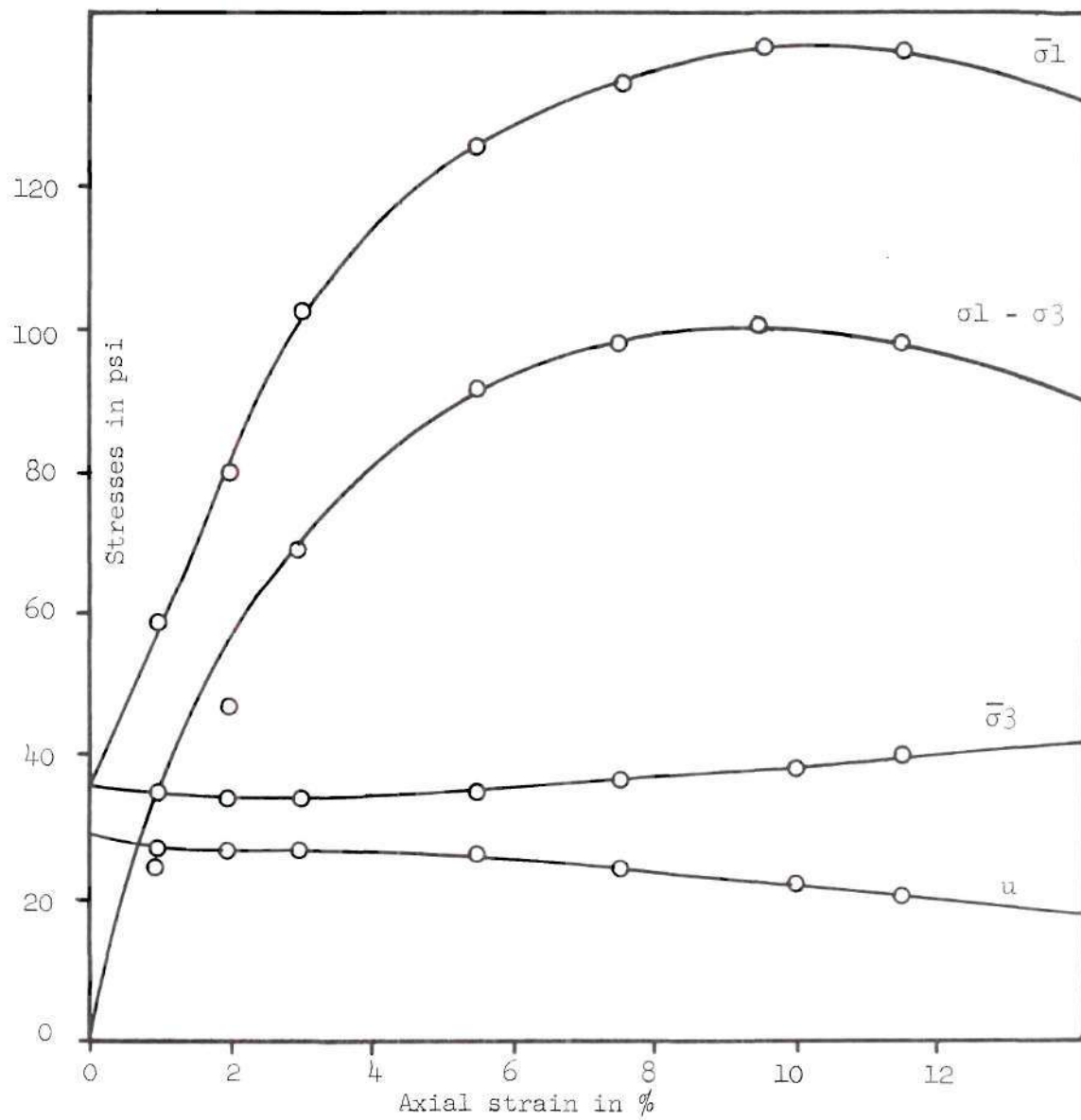


Figure 95. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 2.0
 All around Pressure: 60 psi

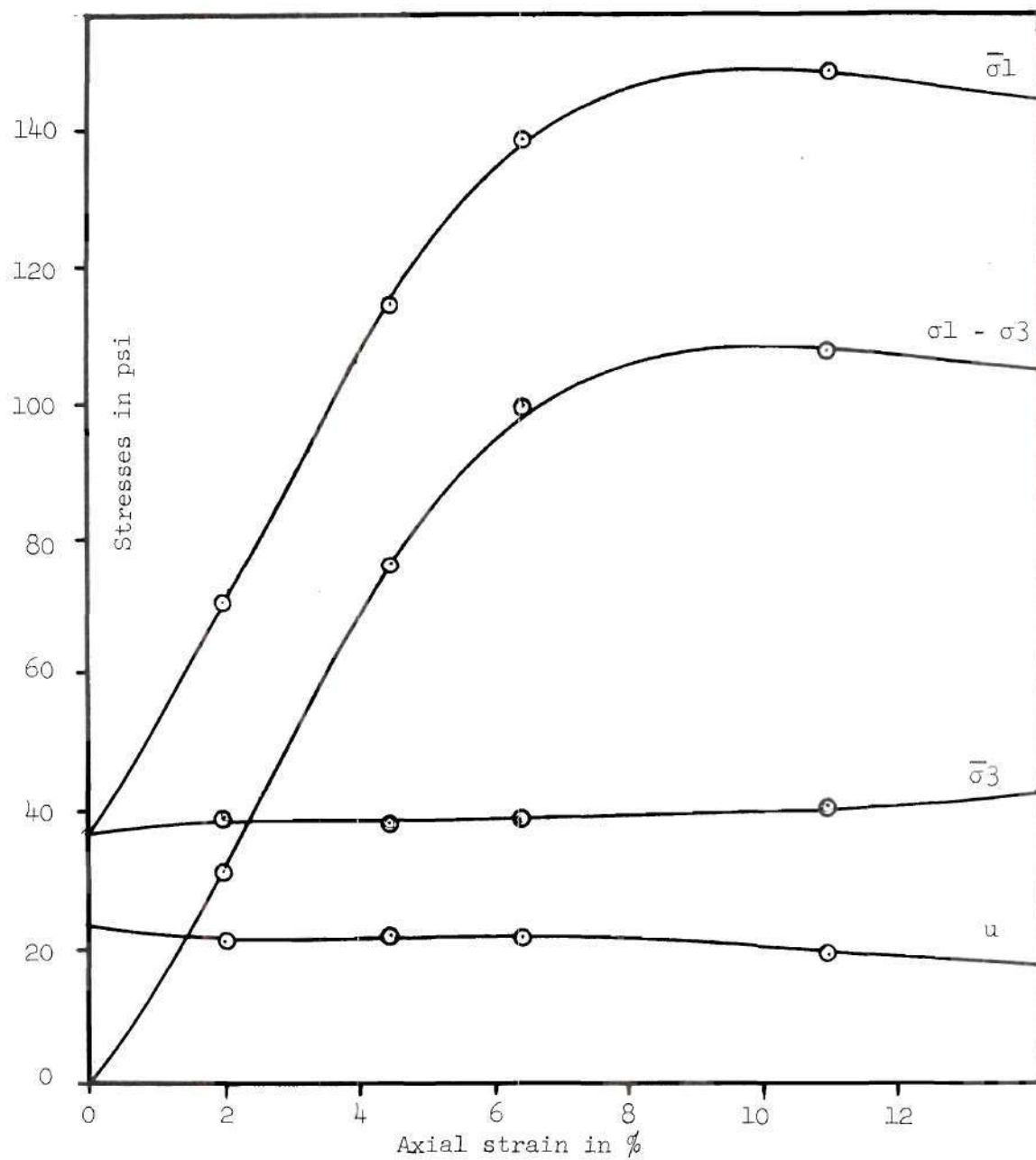


Figure 96. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 2.0
 All around Pressure: 75 psi

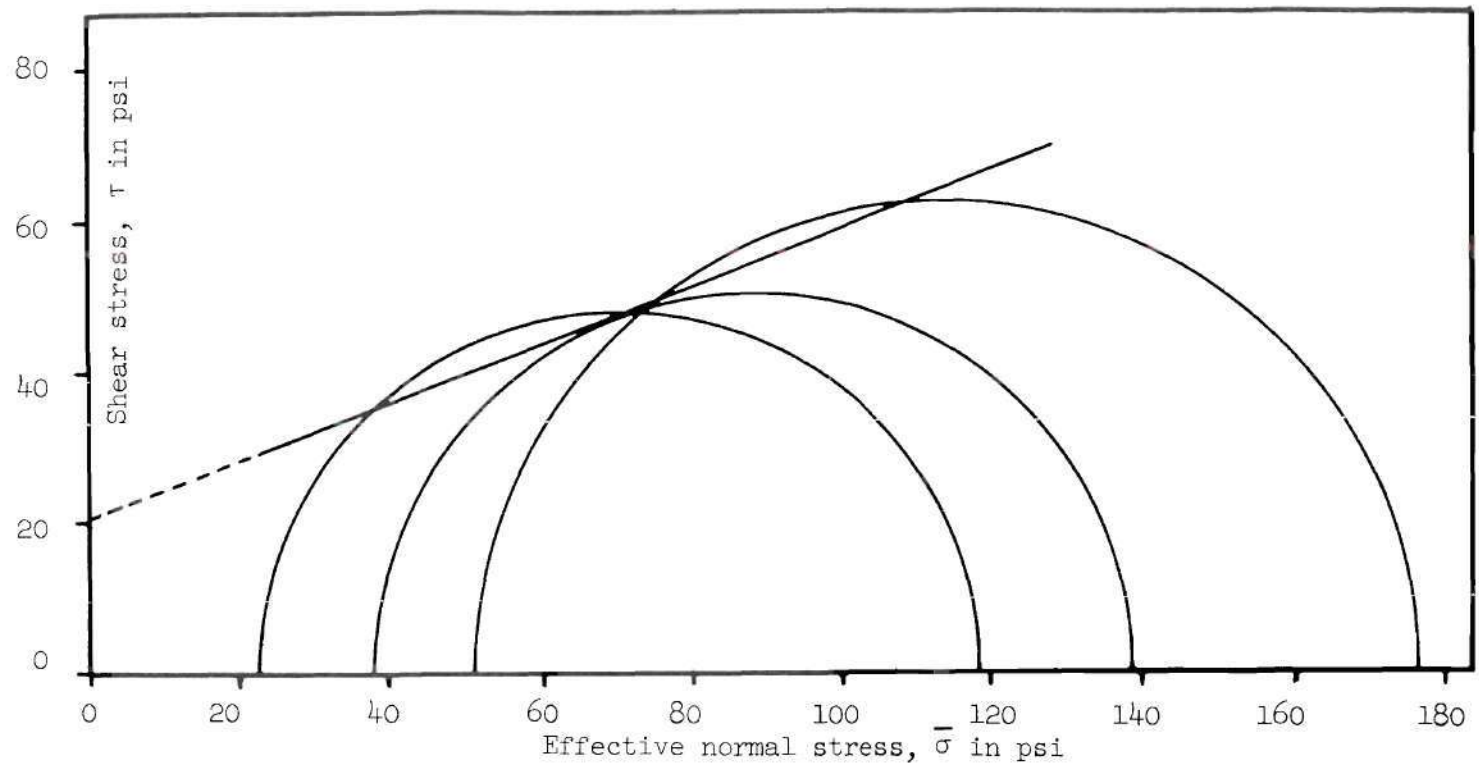


Figure 97. Mohr Circles
Admixture: Alkanol B
Percent Admixture: 2.0

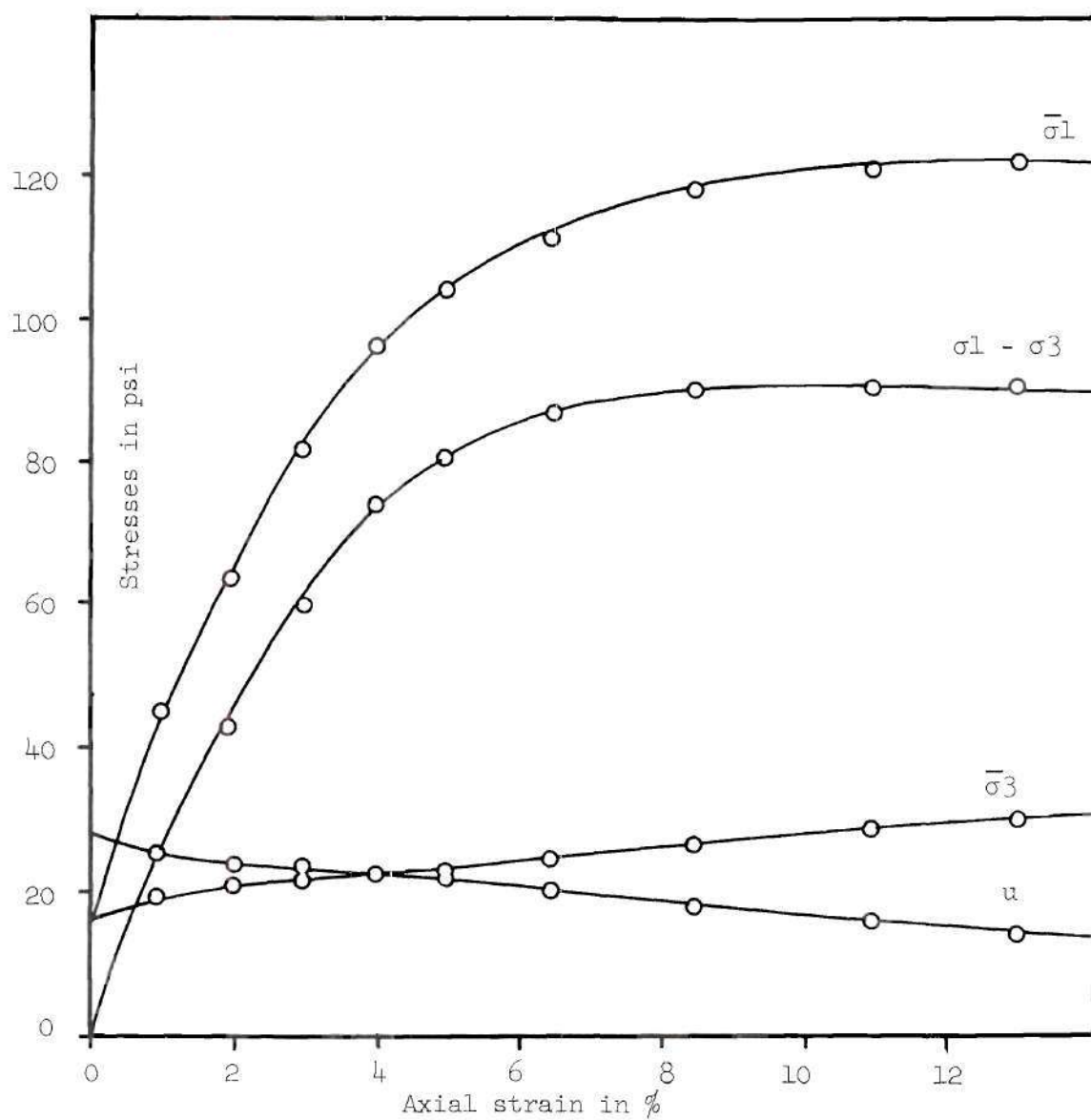


Figure 98. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 3.0
 All around Pressure: 45 psi

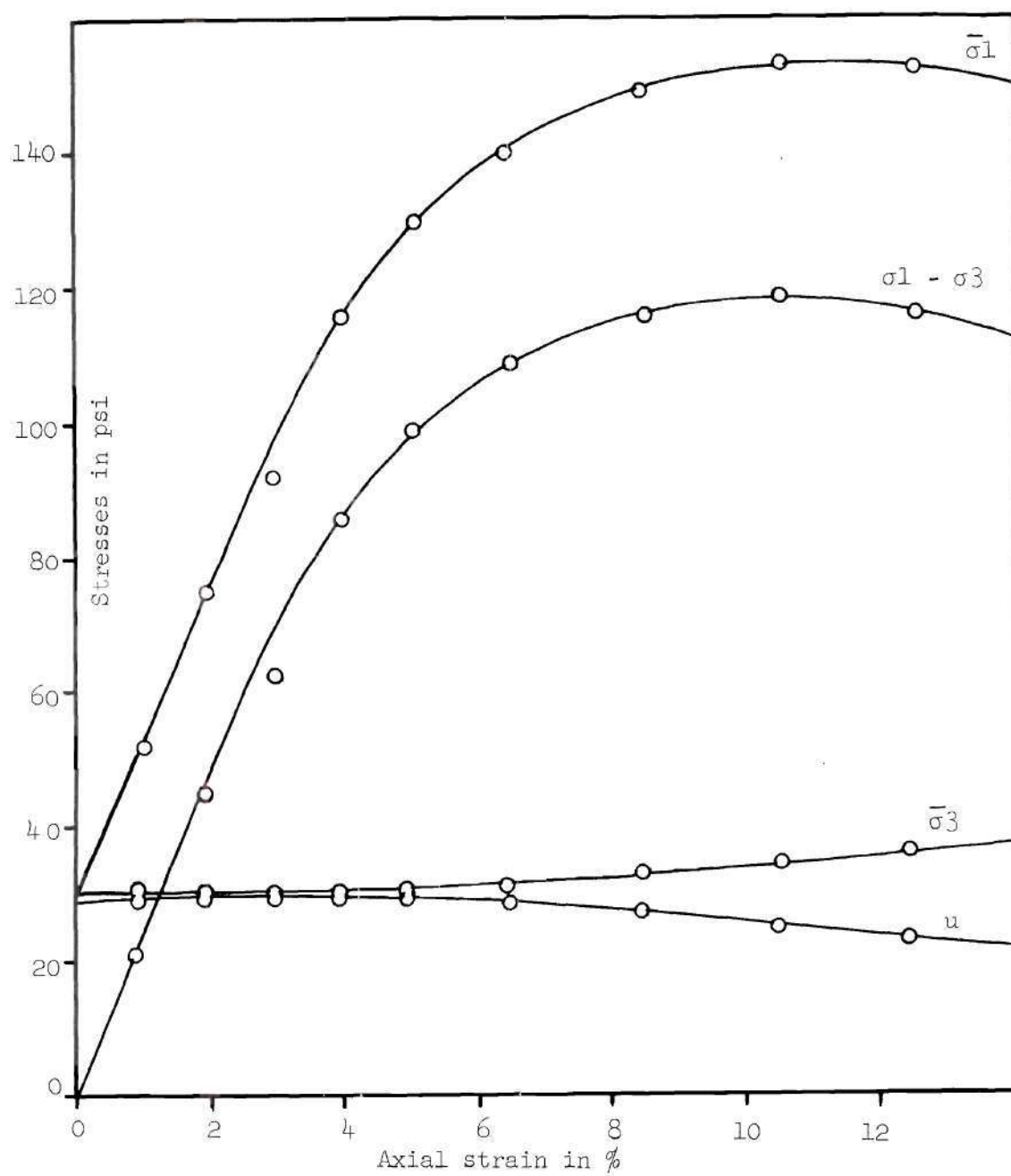


Figure 99. Triaxial Compression Test
 Admixture: Alkanol B
 Percent Admixture: 3.0
 All around Pressure: 60 psi

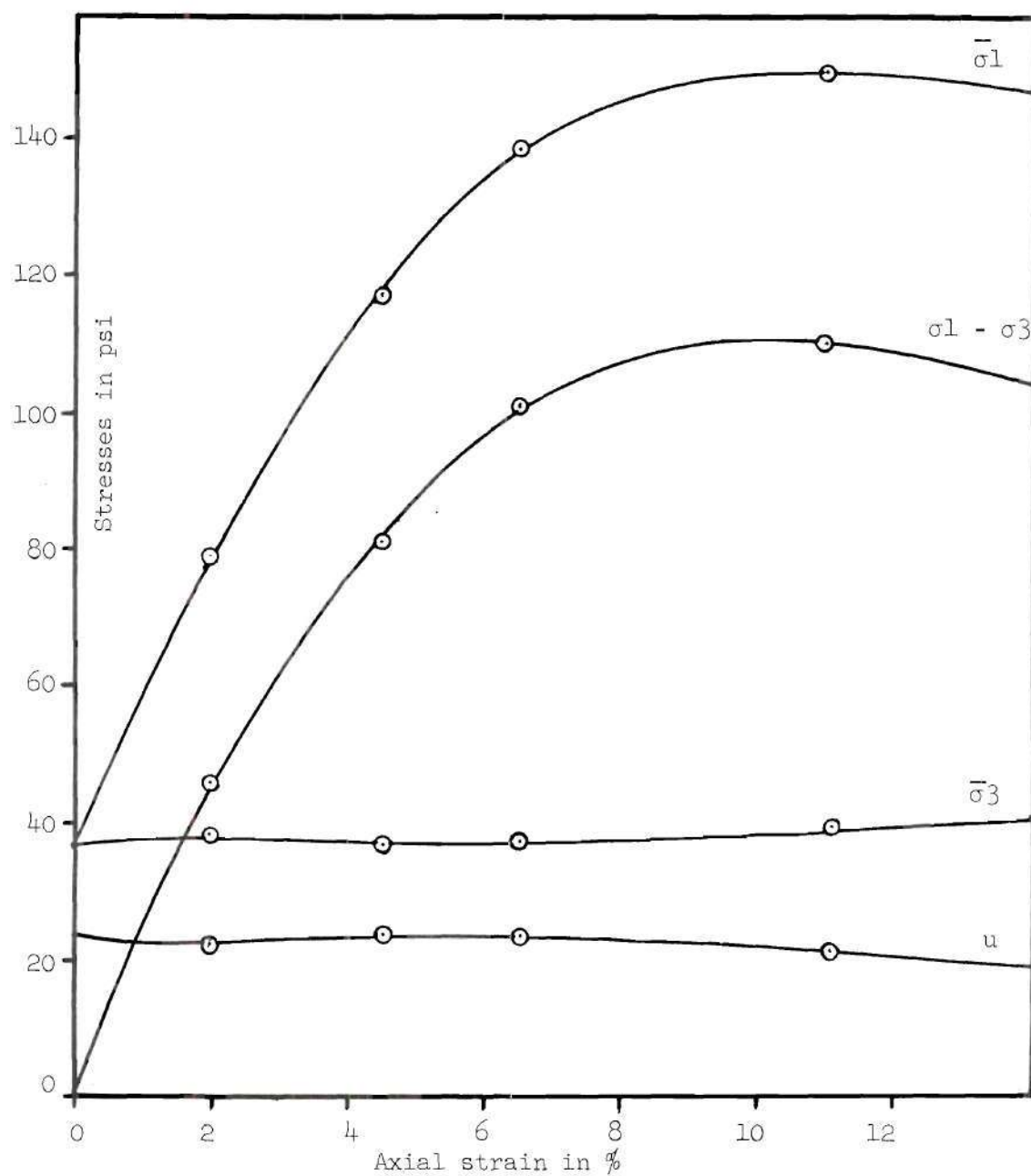


Figure 100. Triaxial Compression Test
 Admixture Alkanol B
 Percent Admixture: 3.0
 All around Pressure: 75 psi

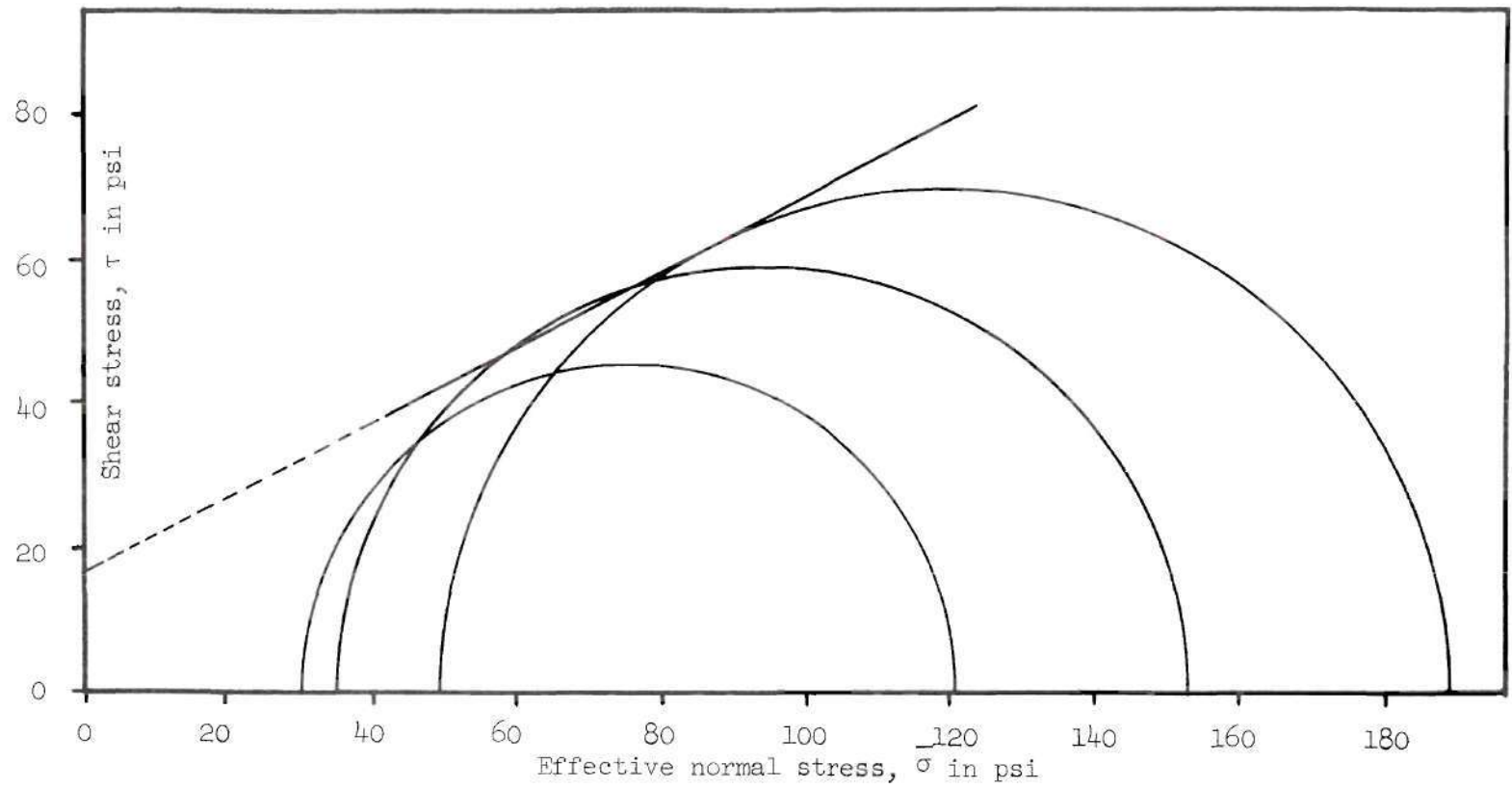


Figure 101. Mohr Circles
Admixture: Alkanol B
Percent Admixture: 3.0

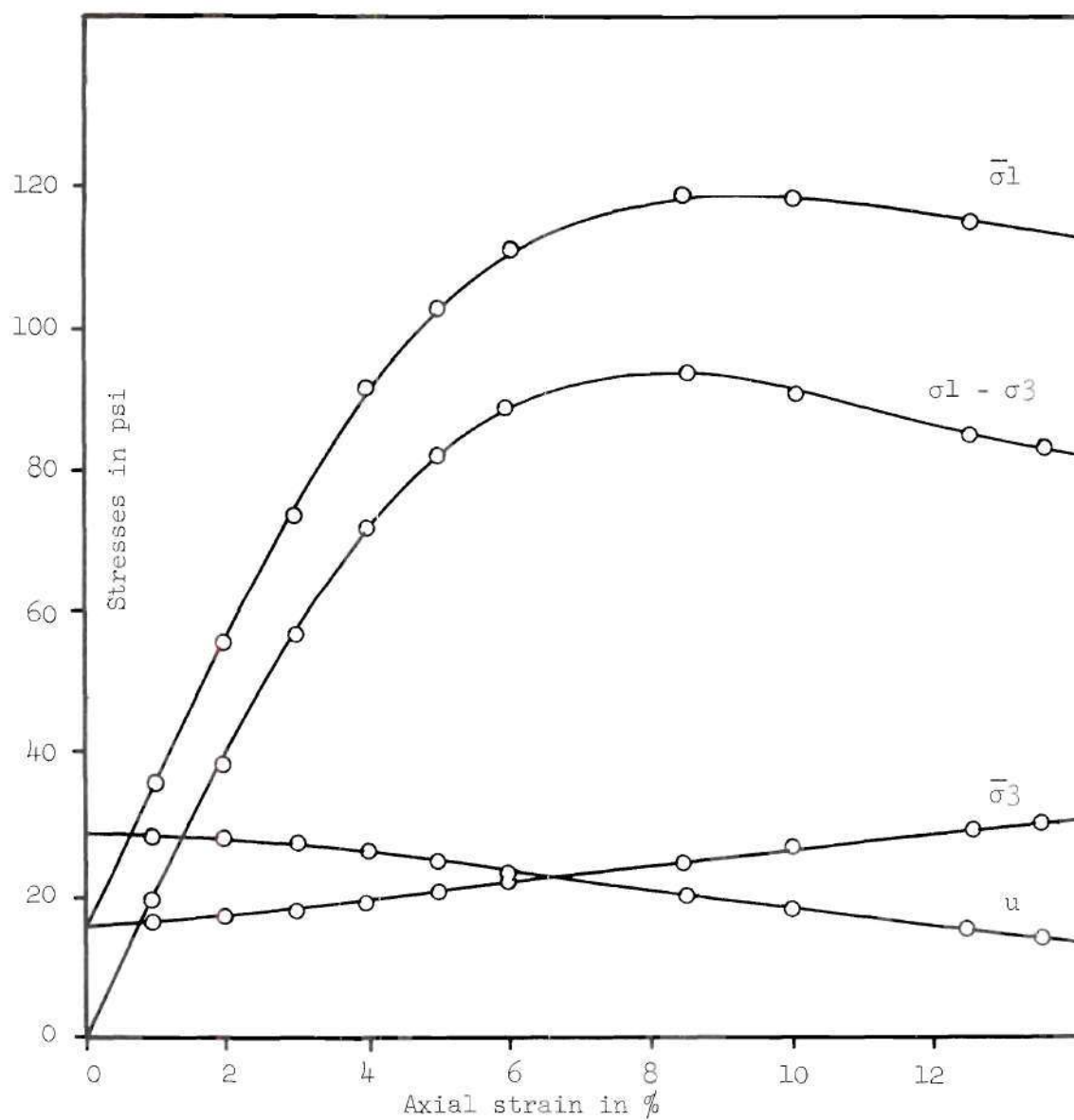


Figure 102. Triaxial Compression Test
 Admixture: Naconol Beads
 Percent Admixture: 0.25
 All around Pressure: 45 psi

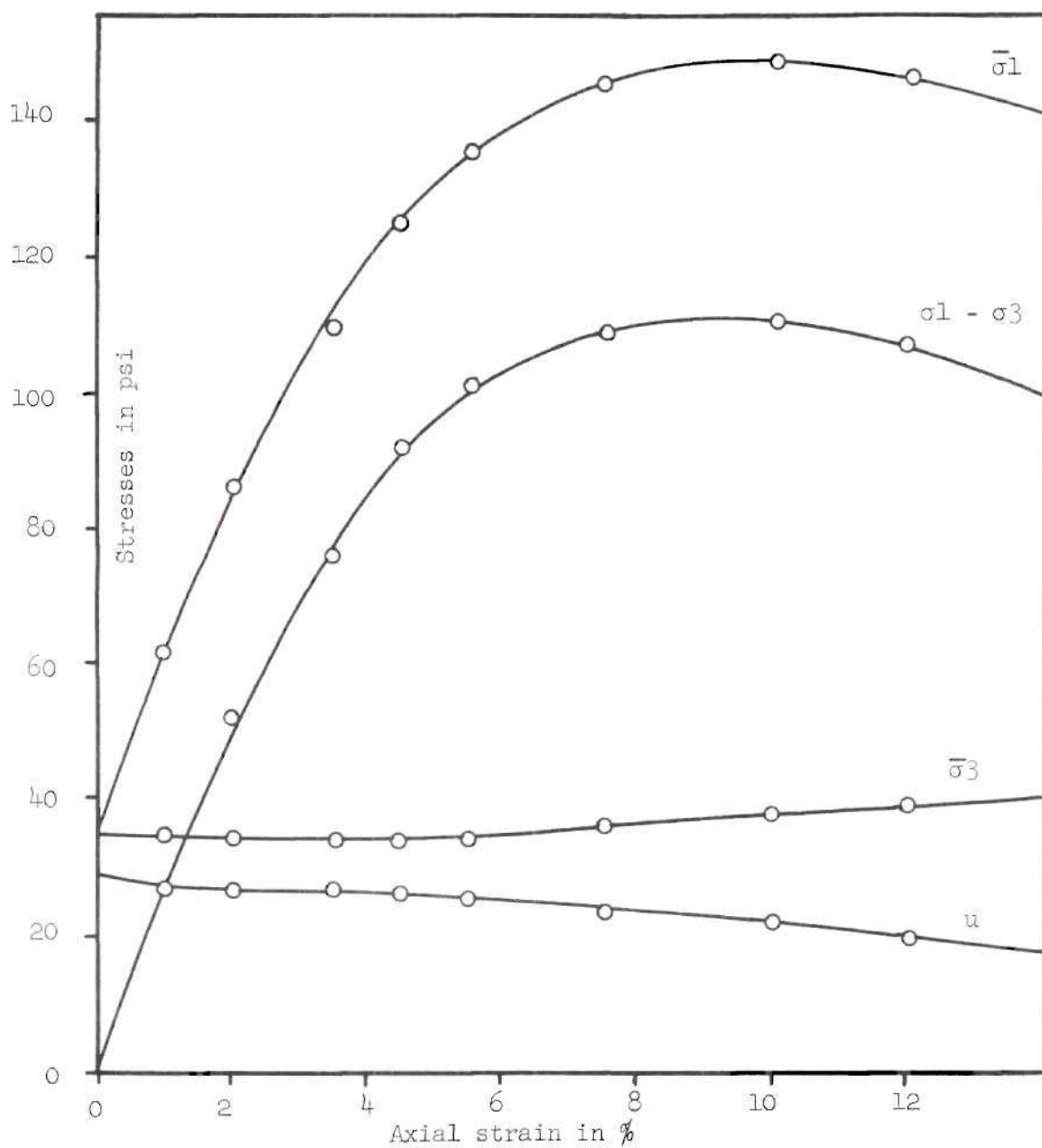


Figure 103. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 0.25
 All around Pressure: 60 psi

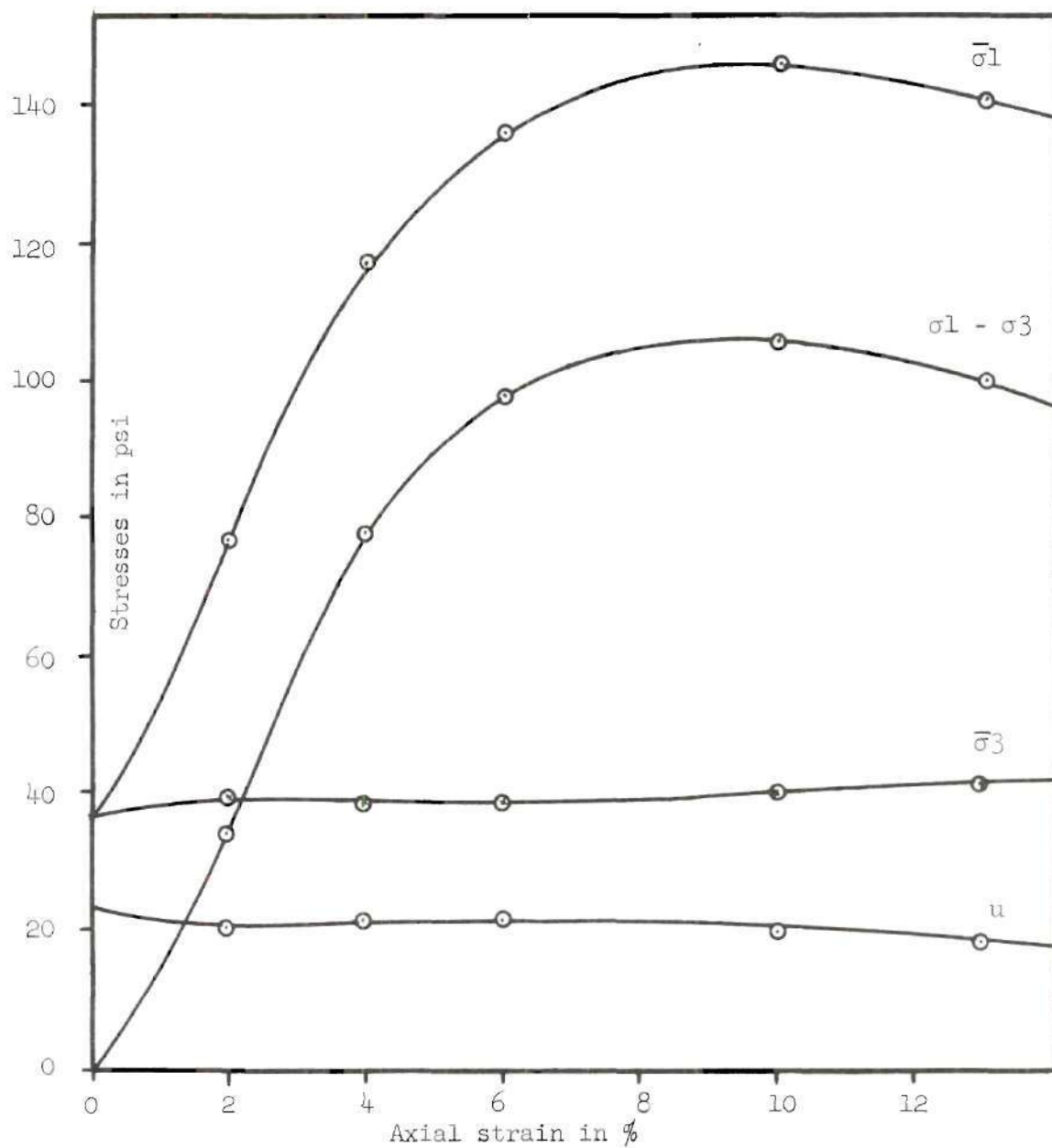


Figure 104. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 0.25
 All around Pressure: 75 psi

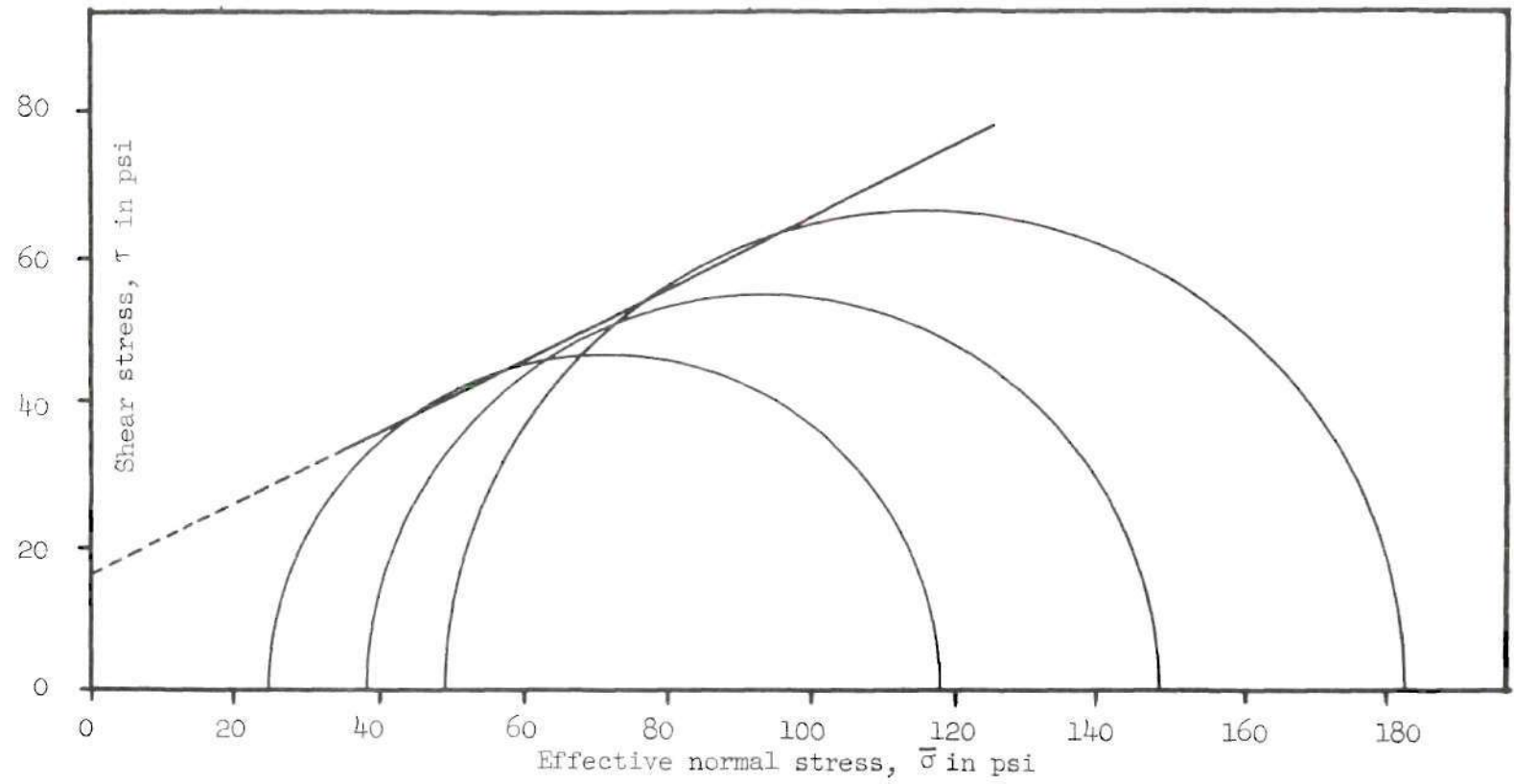


Figure 105. Mohr Circles
 Admixture: Nacconol Beads
 Percent Admixture: 0.25

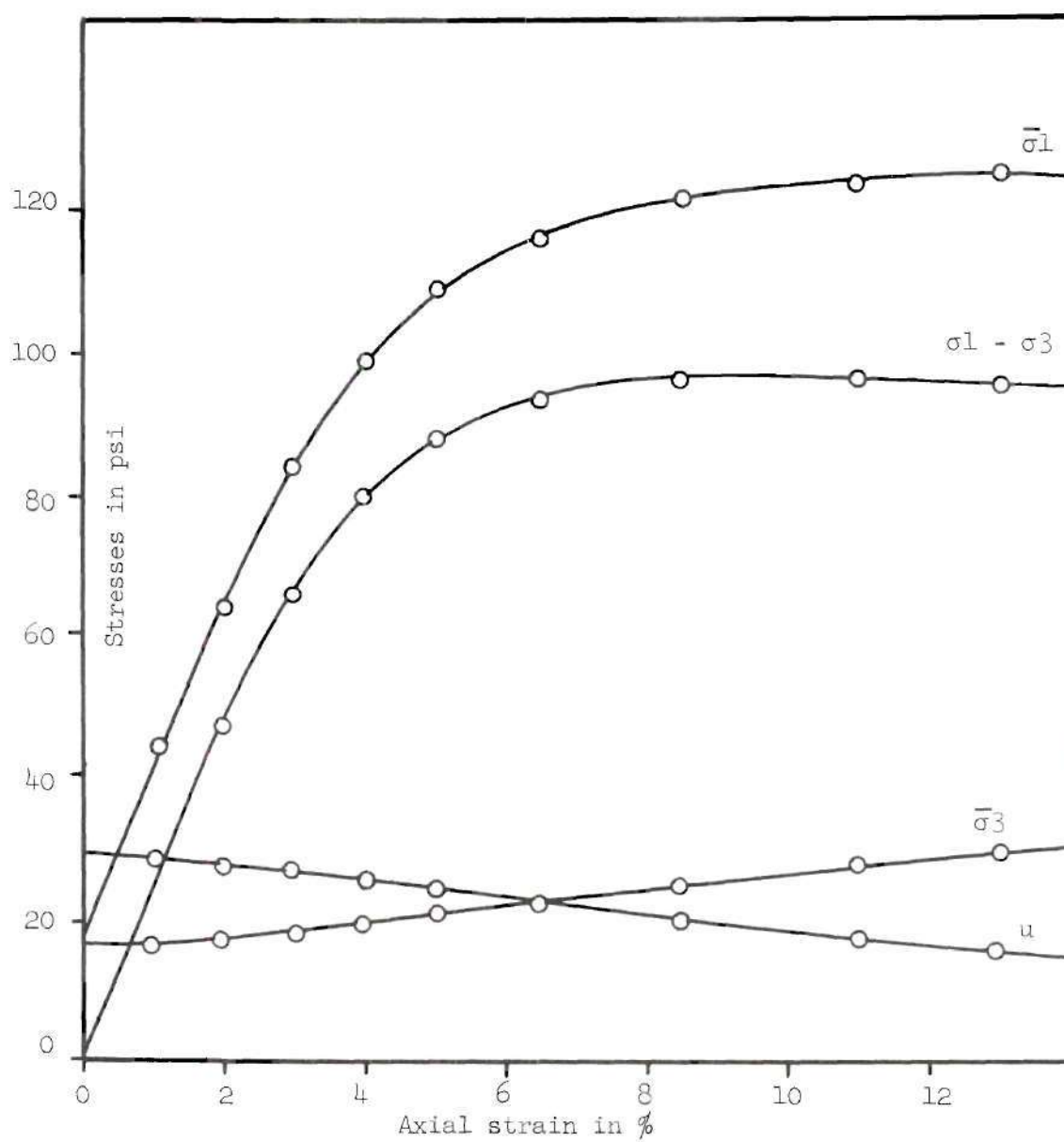


Figure 106. Triaxial Compression Tests
 Admixture: Nacconol Beads
 Percent Admixture: 0.5
 All around Pressure: 45 psi

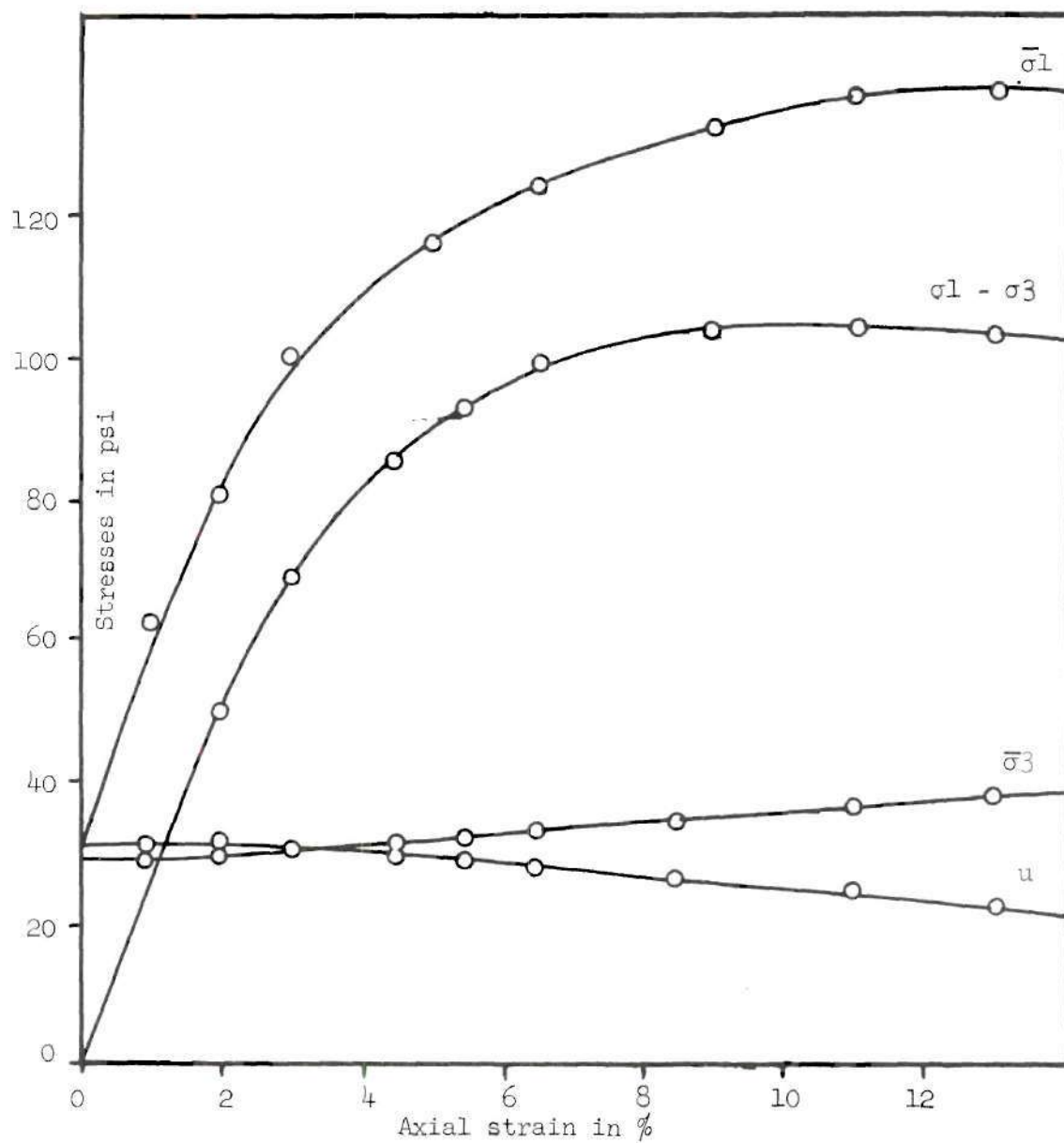


Figure 107. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 0.5
 All around Pressure: 60 psi

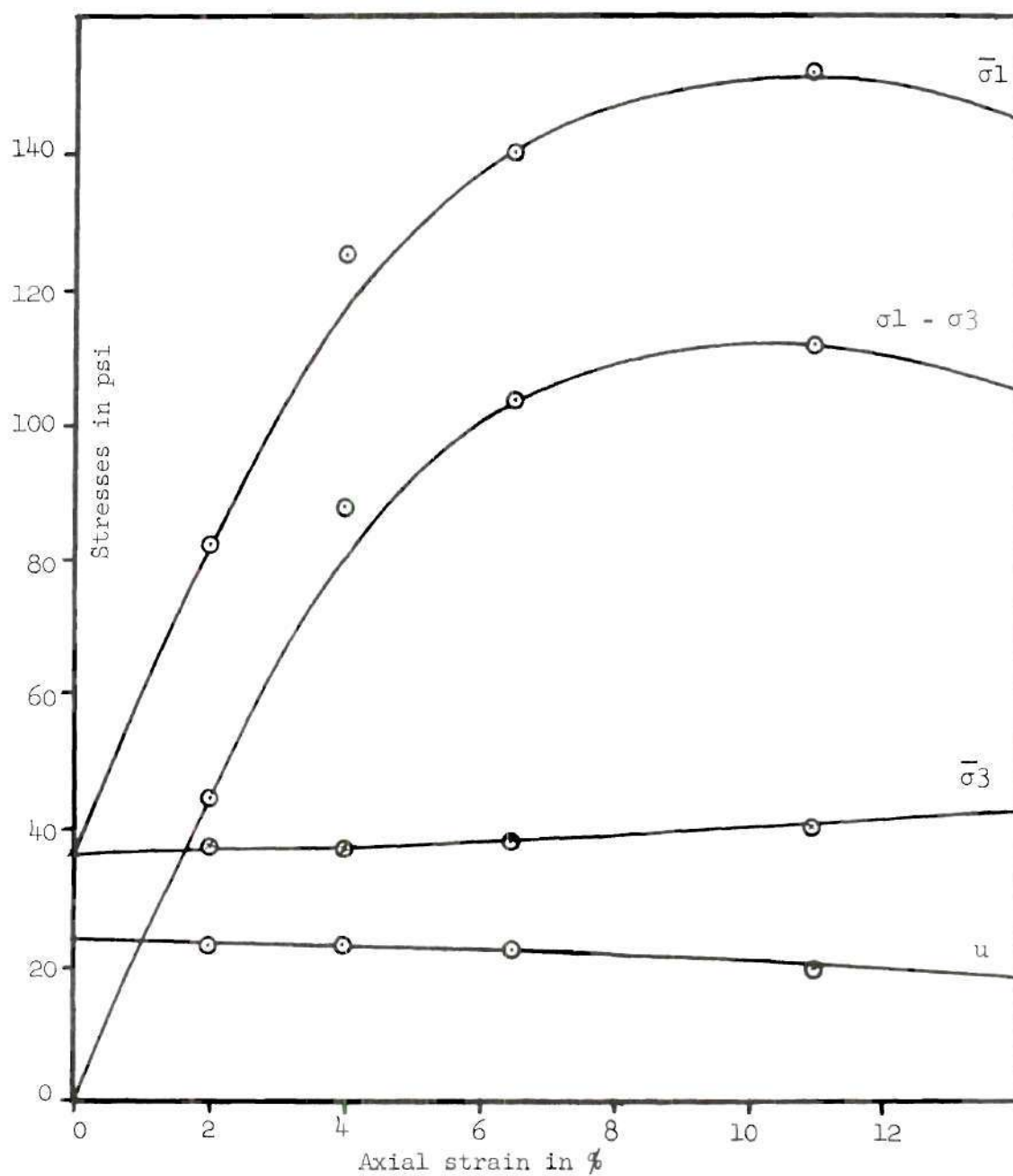


Figure 108. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 0.5
 All around Pressure: 75 psi

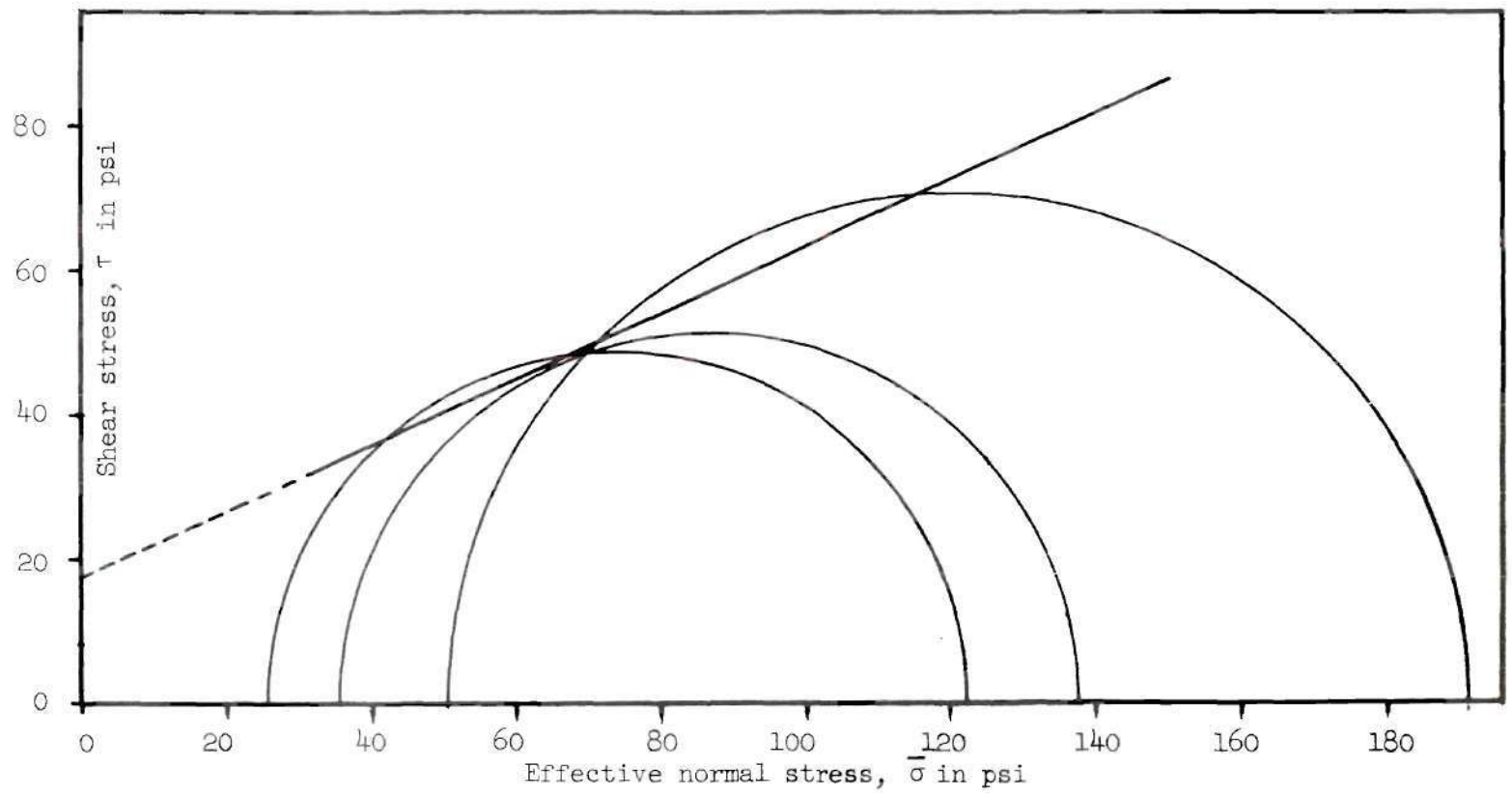


Figure 109. Mohr Circles
 Admixture: Nacconol Beads
 Percent Admixture: 0.5

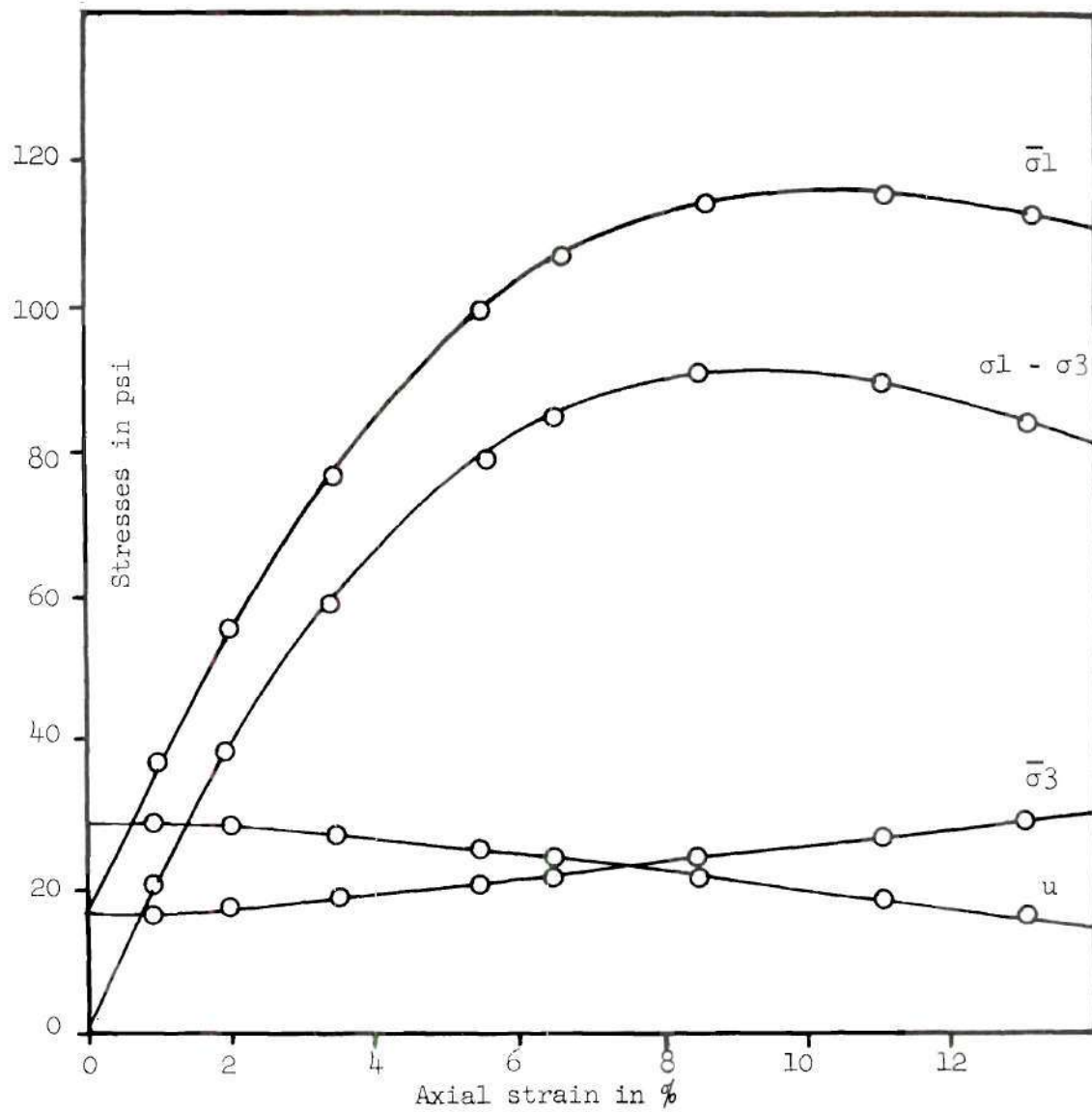


Figure 110. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 0.75
 All around Pressure: 45 psi

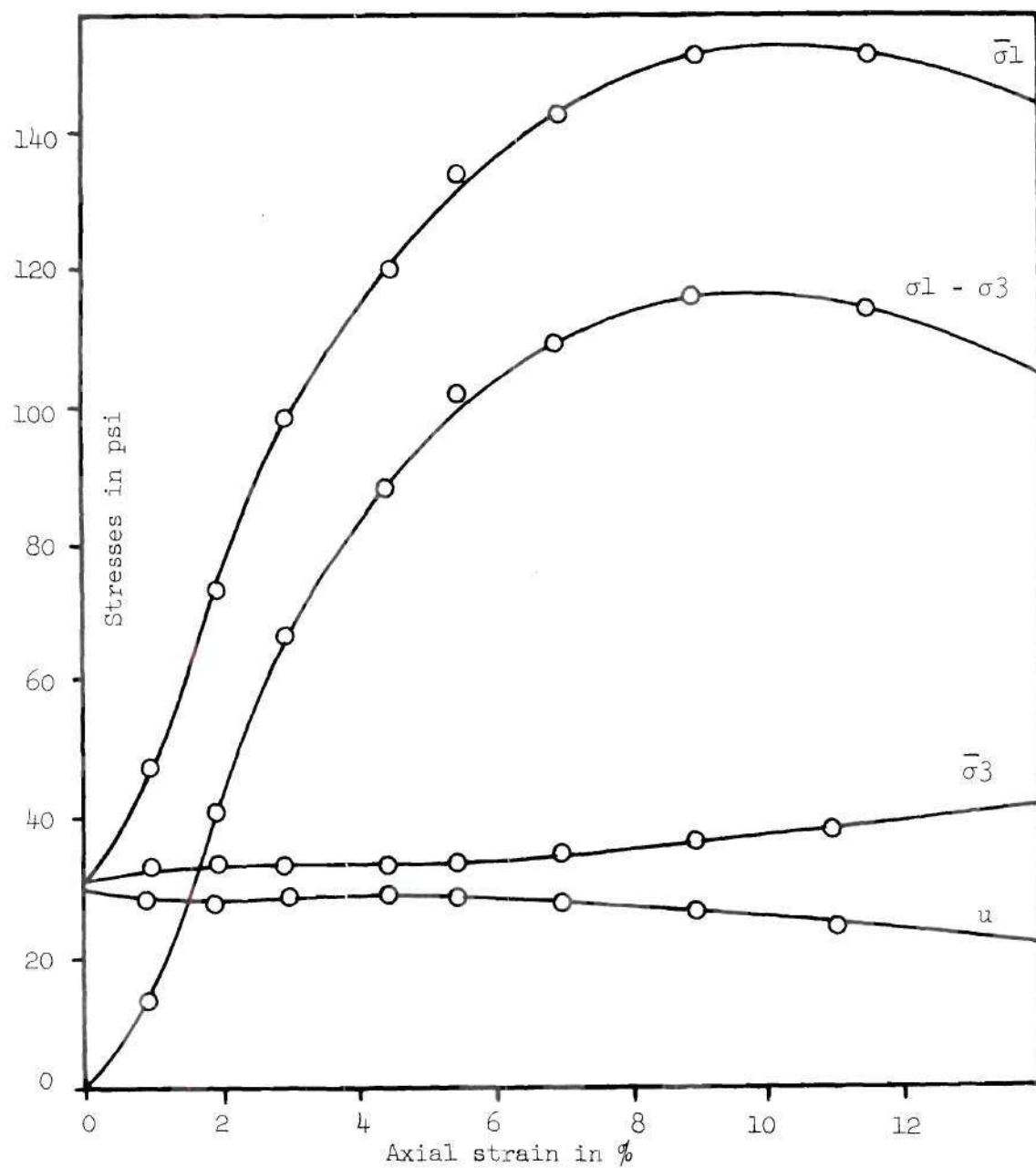


Figure 111. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 0.75
 All around Pressure: 60 psi

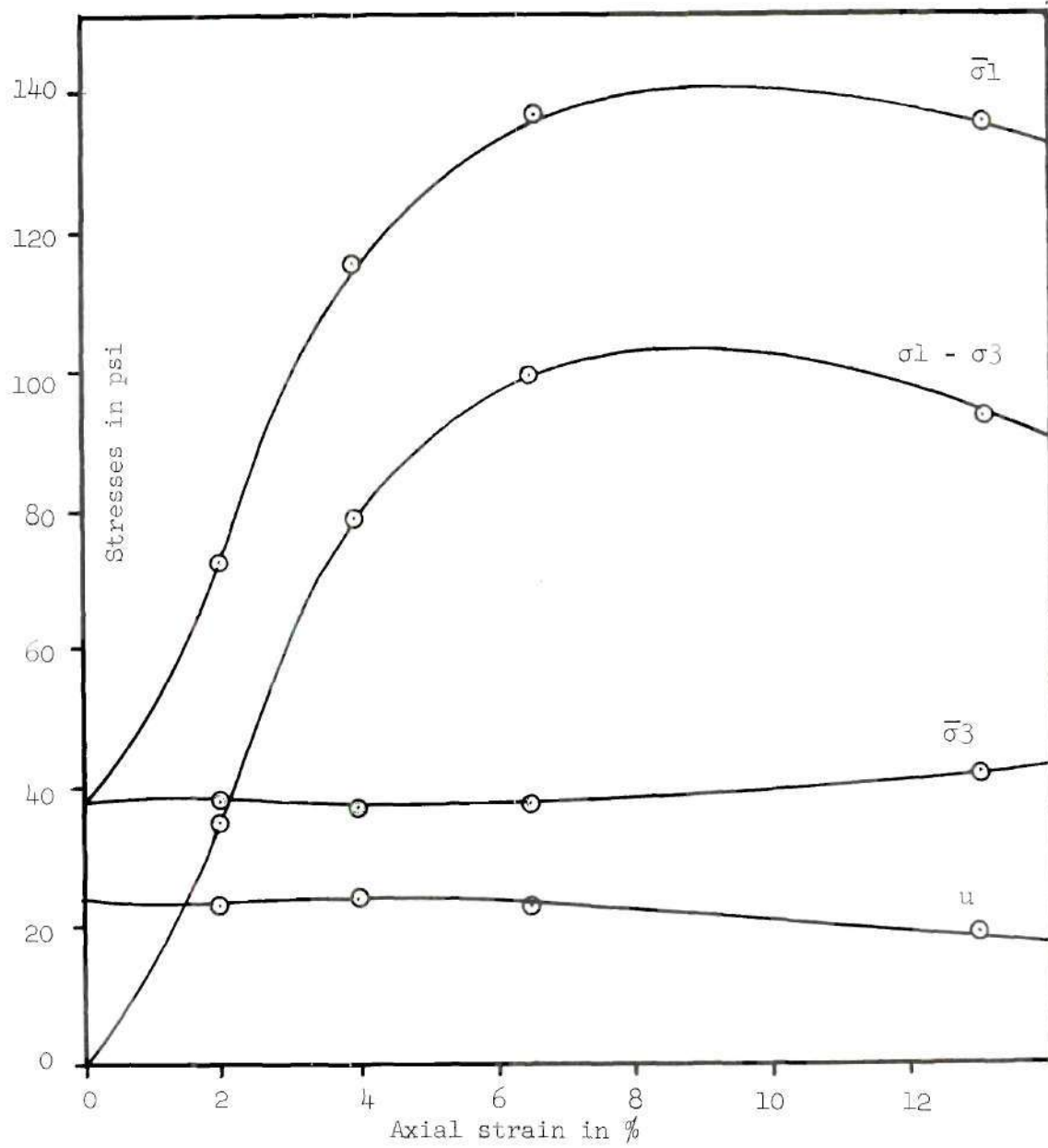


Figure 112. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 0.75
 All around Pressure: 75 psi

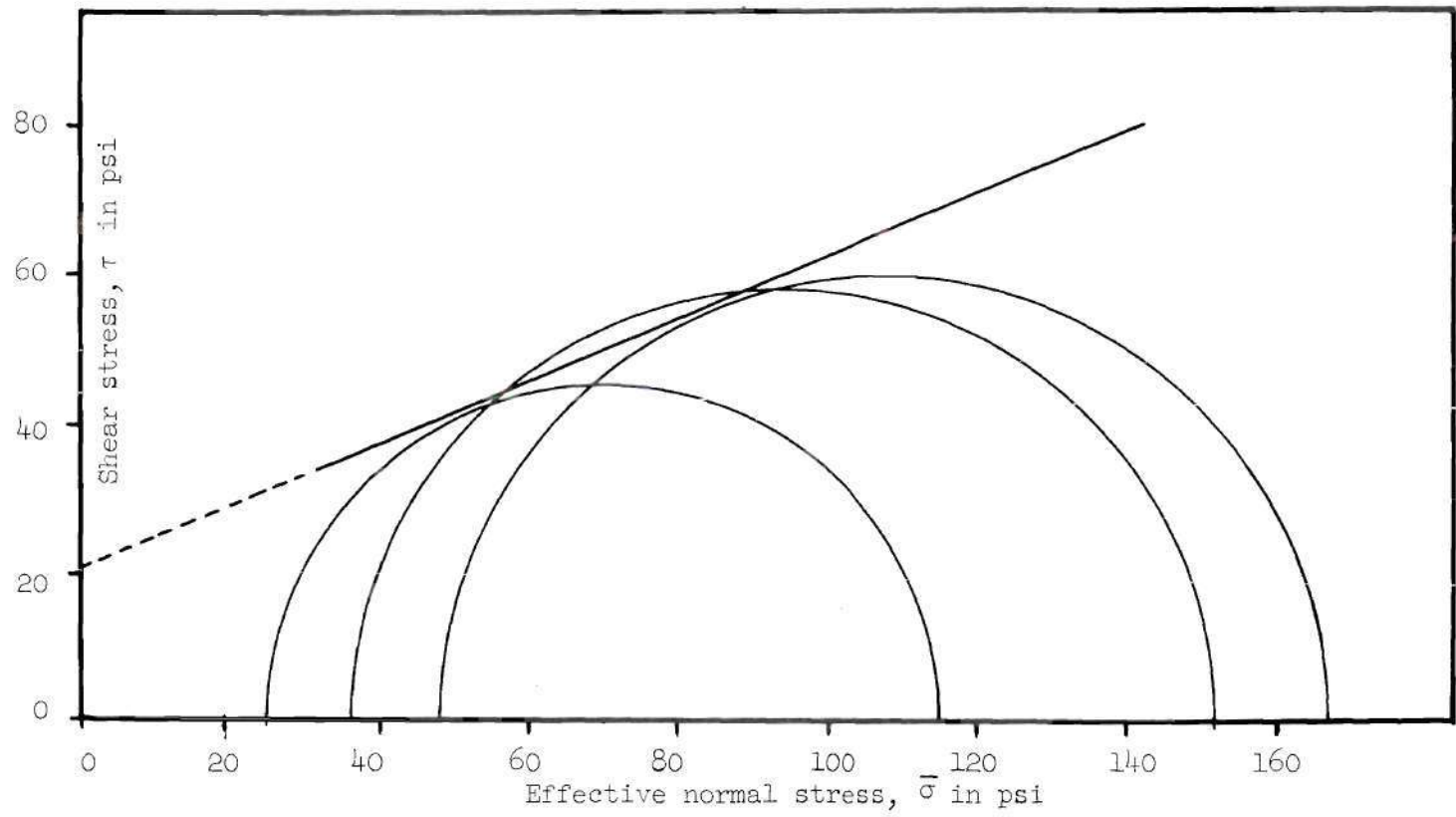


Figure 113. Mohr Circles
 Admixture: Nacconol Beads
 Percent Admixture: 0.75

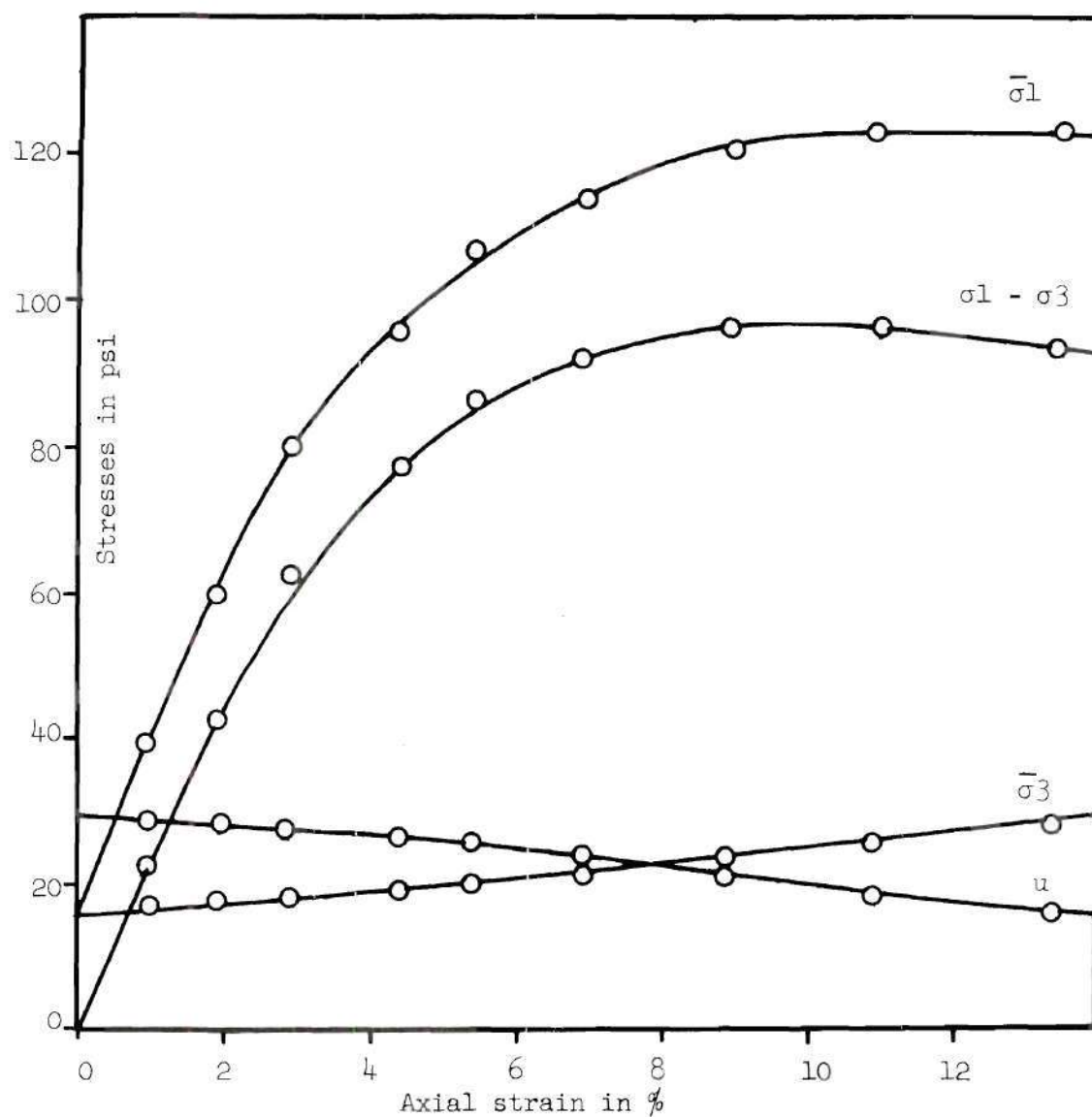


Figure 114. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 1.0
 All around Pressure: 45 psi

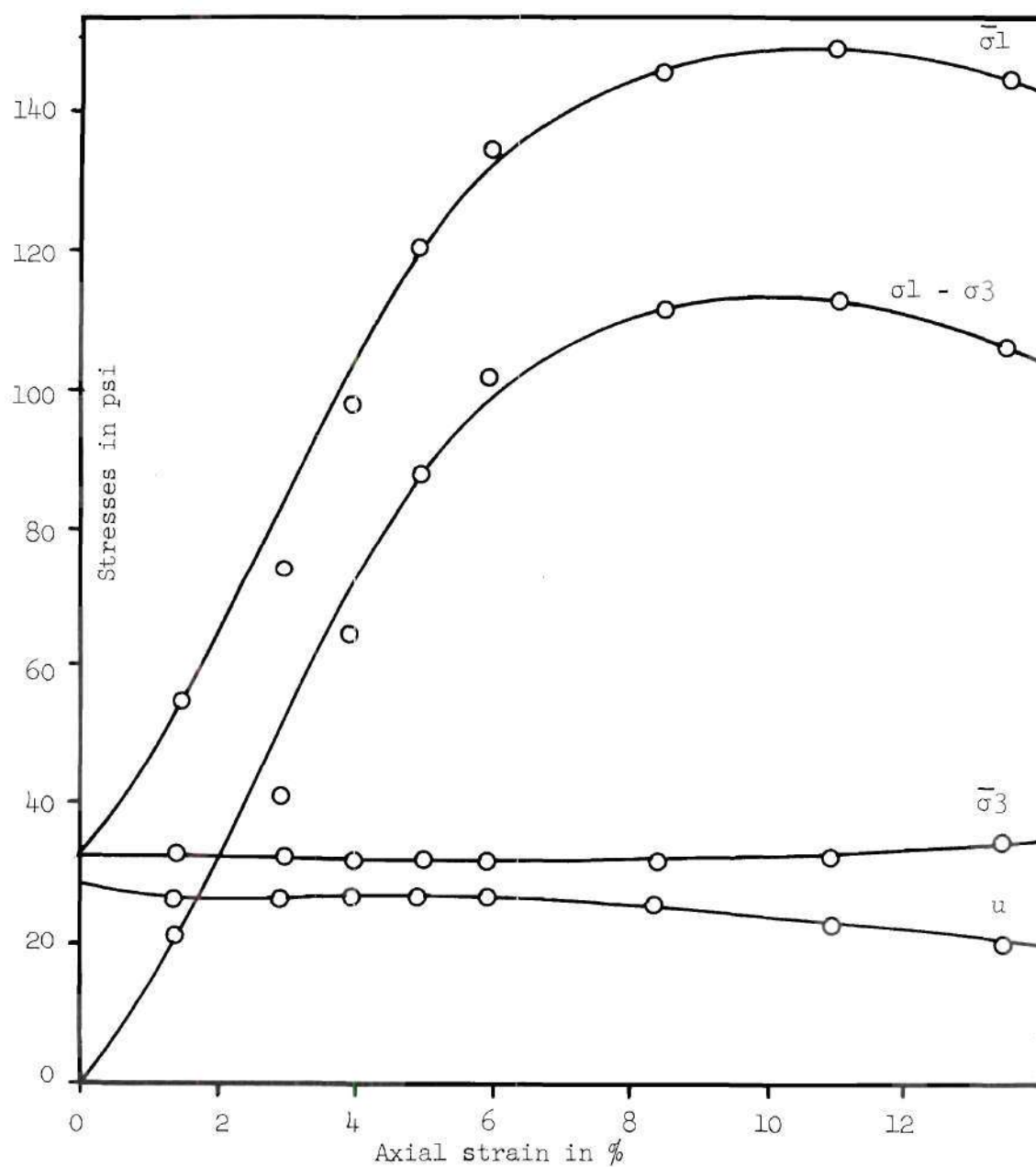


Figure 115. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 1.0
 All around Pressure: 60 psi

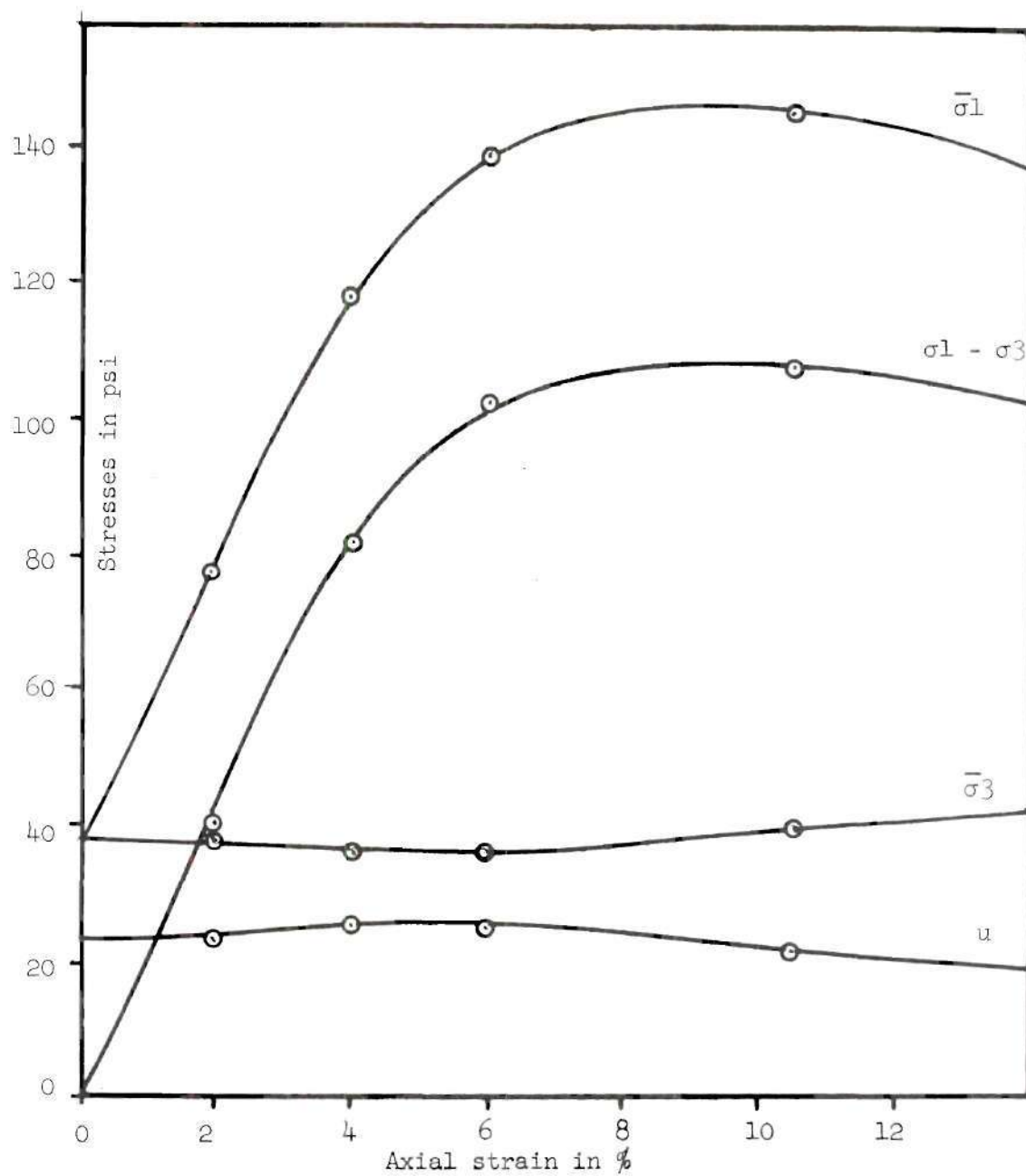


Figure 116. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 1.0
 All around Pressure: 75 psi

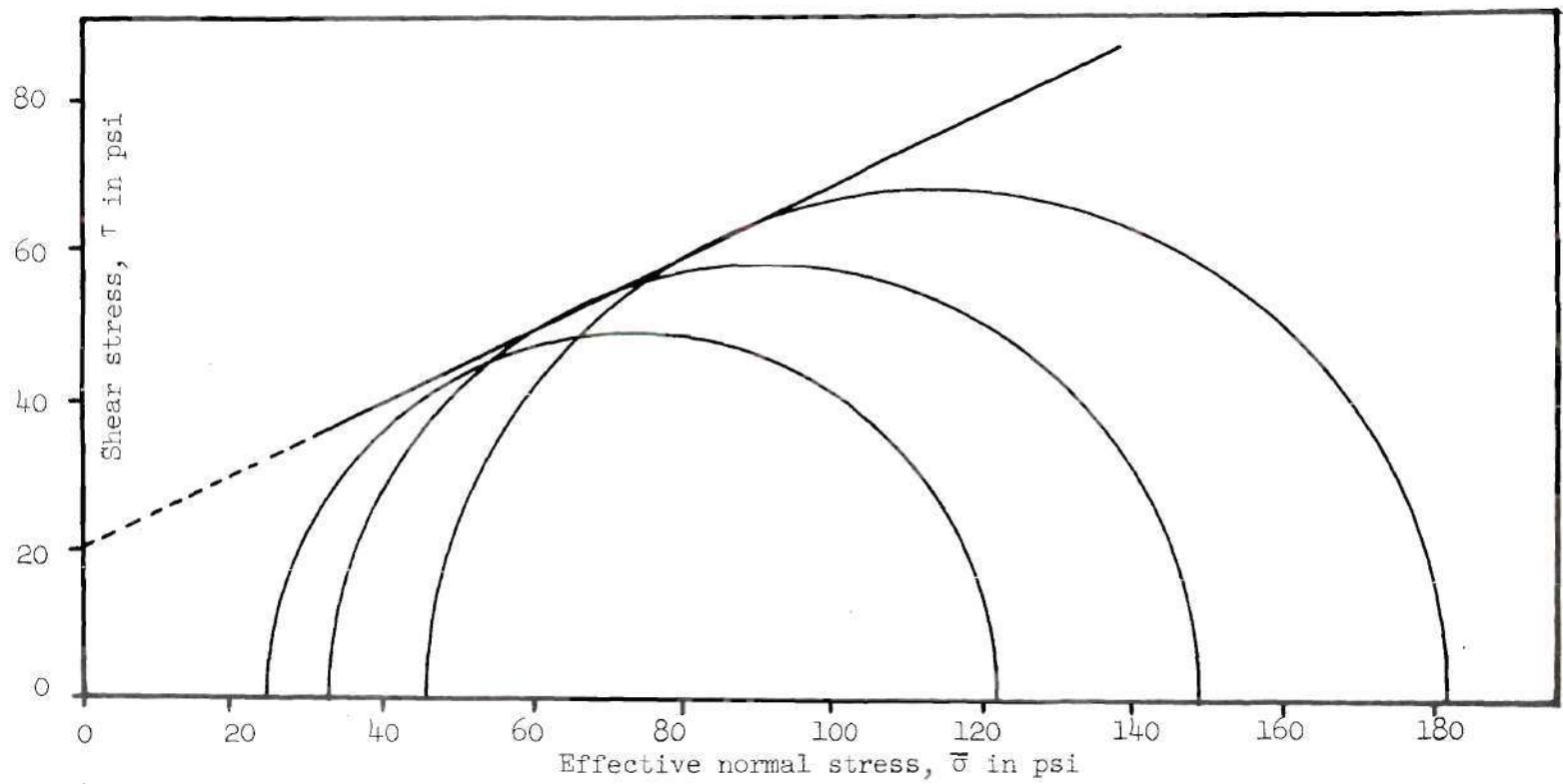


Figure 117. Mohr Circles
 Admixture: Nacconol Beads
 Percent Admixture: 1.0

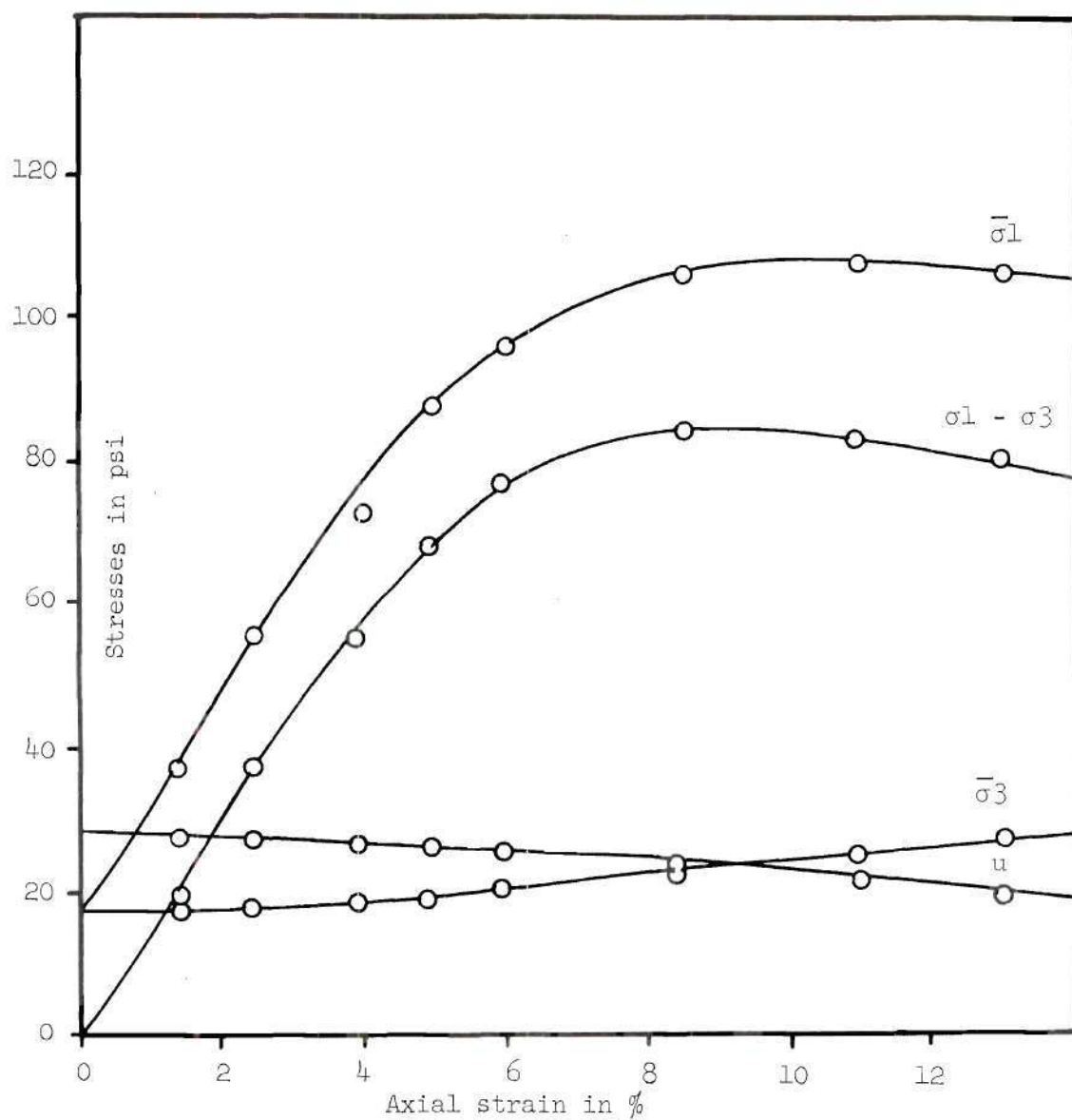


Figure 118. Triaxial Compression Test
Admixture: Nacconol Beads
Percent Admixture: 2.0
All around Pressure. 45 psi

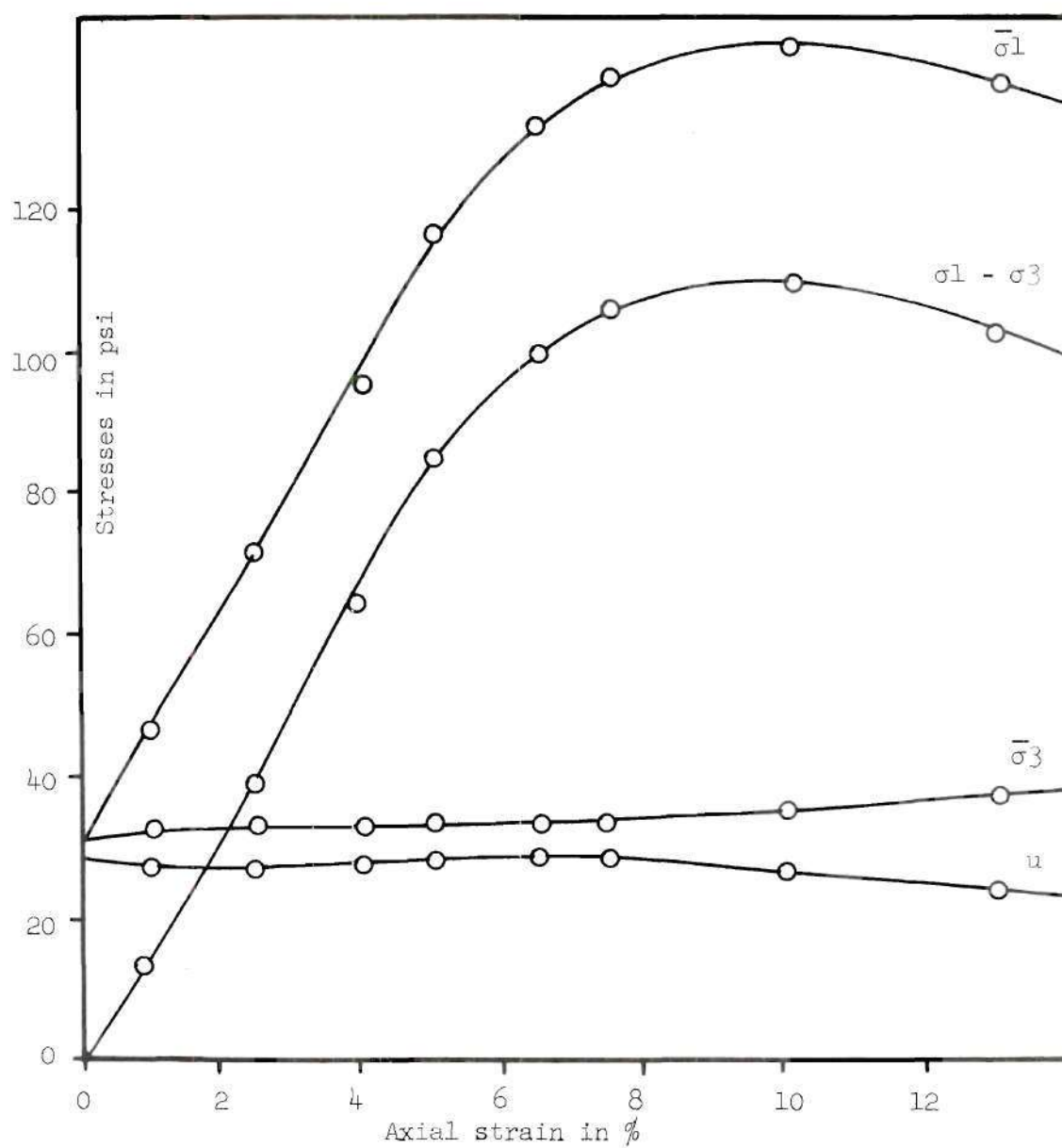


Figure 119. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 2.0
 All around Pressure: 60 psi

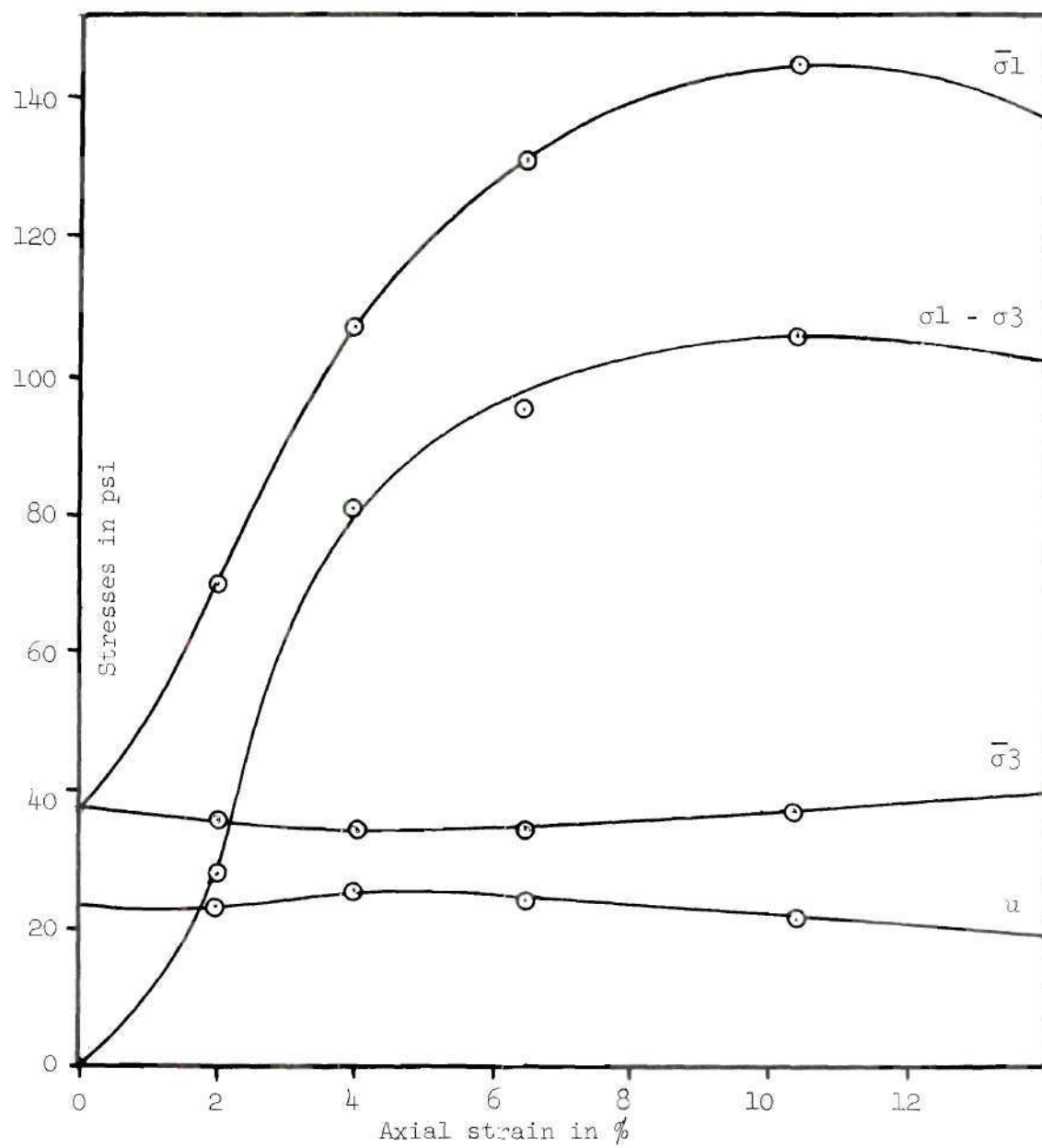


Figure 120. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent A mixture: 2.0
 All around Pressure: 75 psi

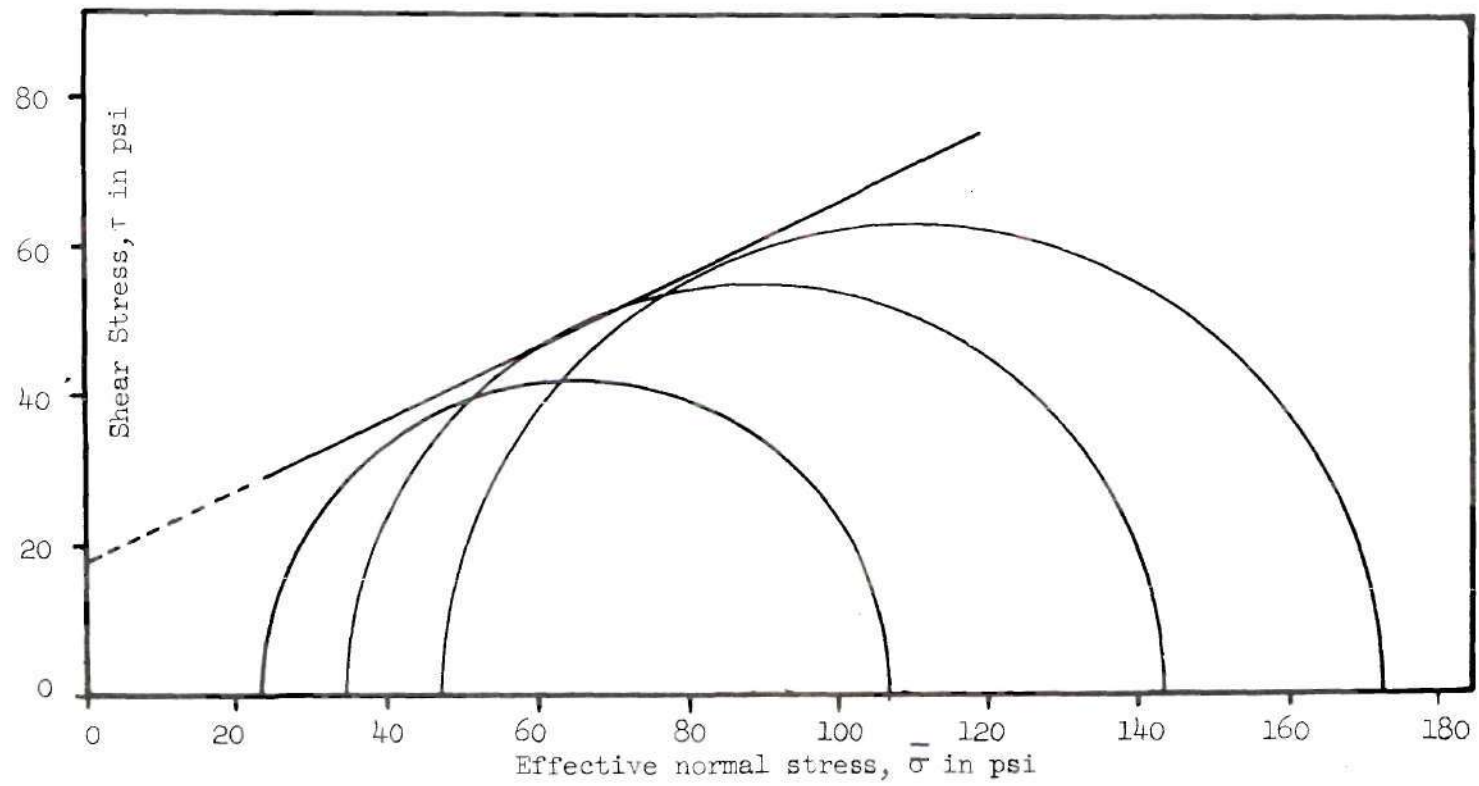


Figure 121. Mohr Circles
 Admixture: Nacconol Beads
 Percent Admixture: 2.0

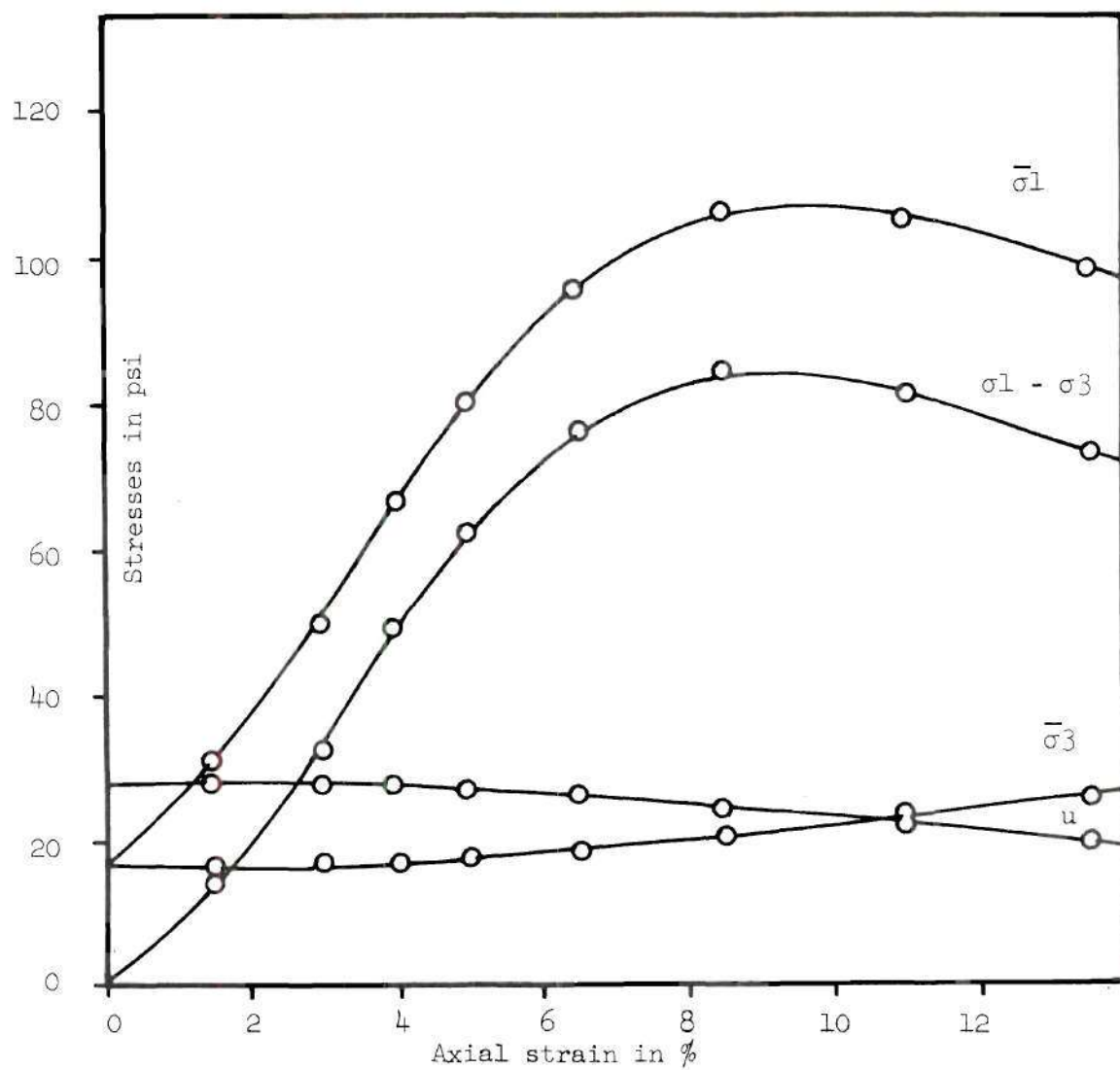


Figure 122. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 3.0
 All around Pressure: 45 psi

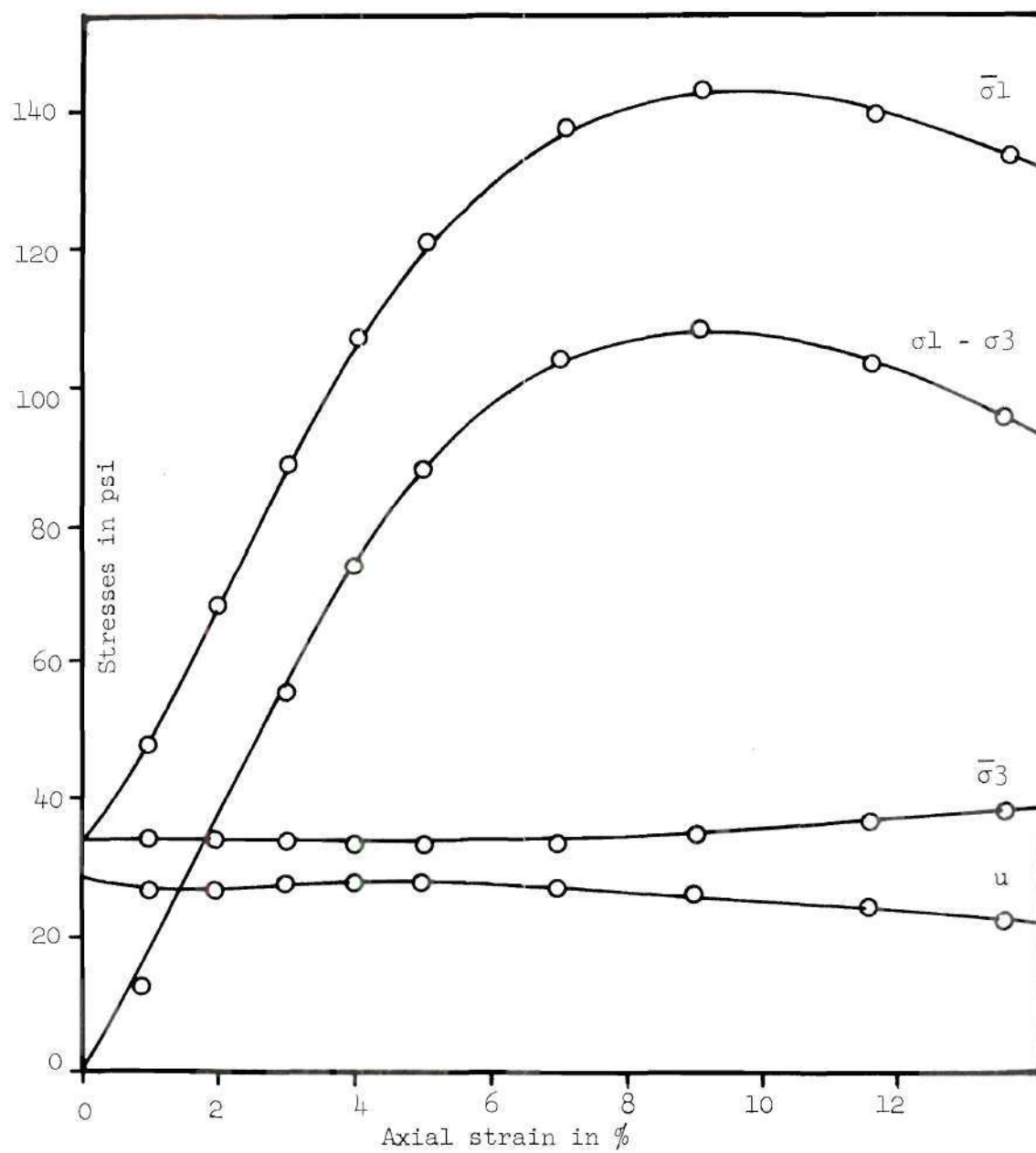


Figure 123. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 3.0
 All around Pressure: 60 psi

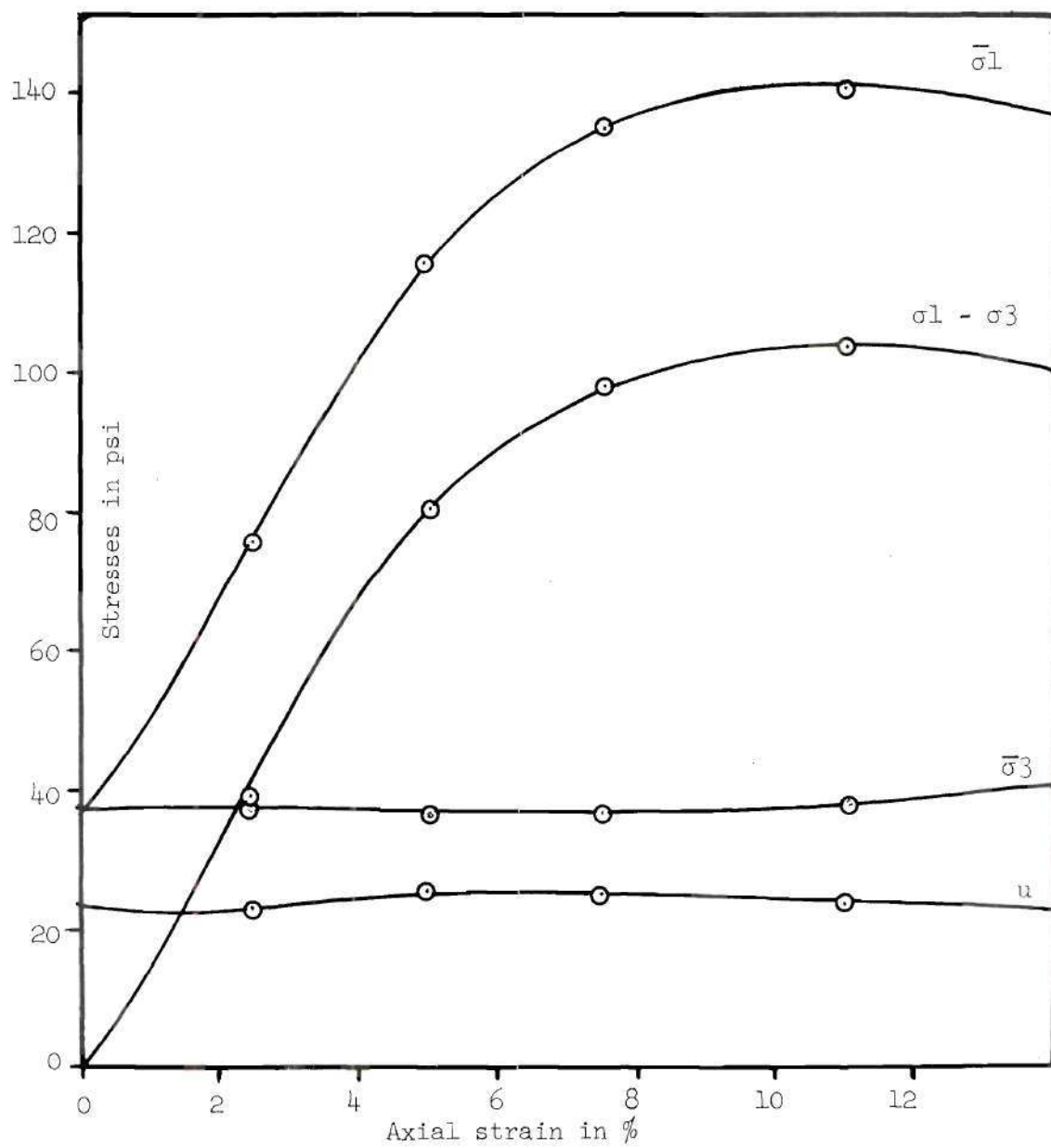


Figure 124. Triaxial Compression Test
 Admixture: Nacconol Beads
 Percent Admixture: 3.0
 All around Pressure: 75 psi

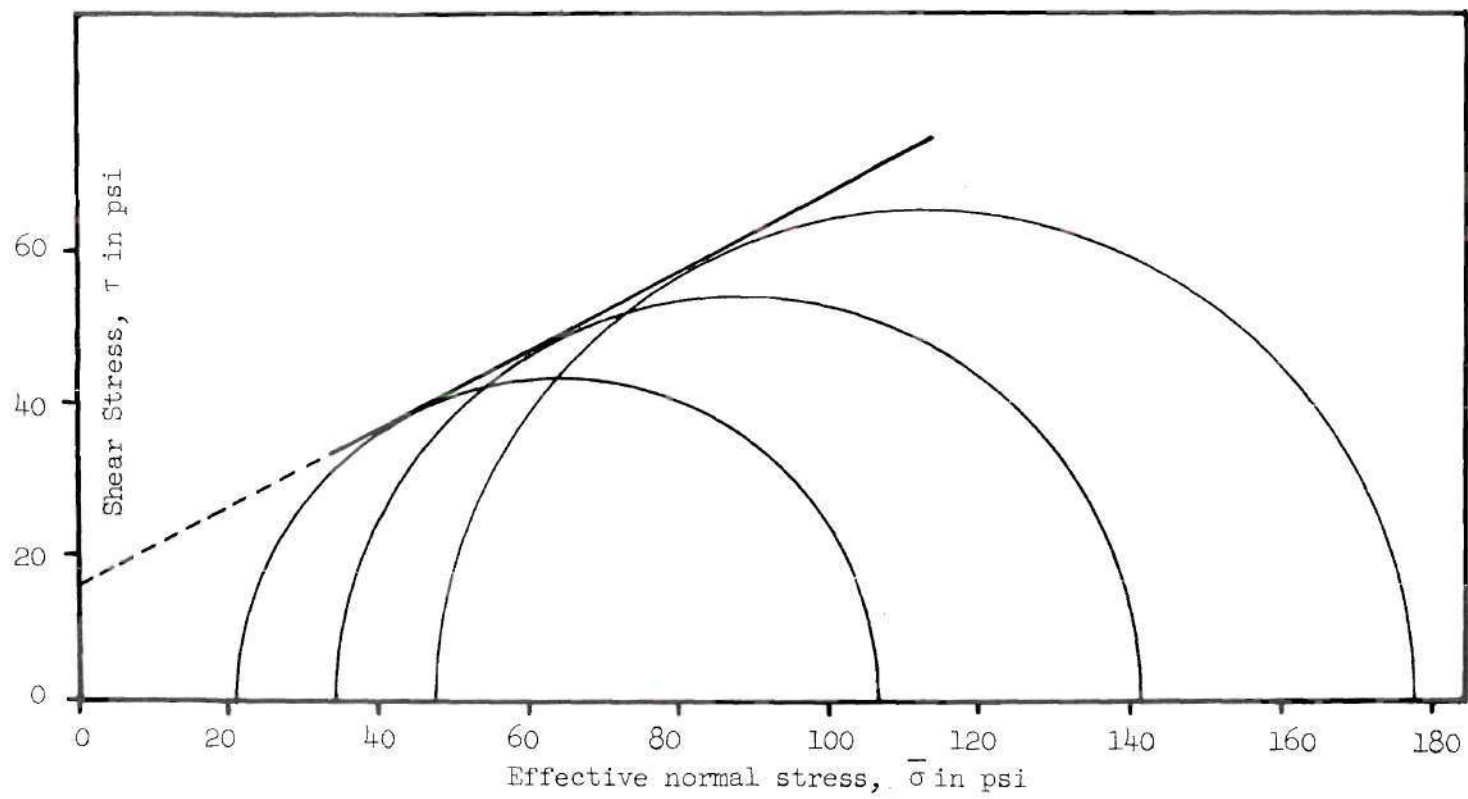


Figure 125. Mohr Circles
 Admixture: Naconol Beads
 Percent Admixture: 3.0

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